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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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ELEMENTS OF DIASTROPHIC HISTORY OF NORTHEASTERN VENEZUELA

BY CLEMENTE GONZÁLEZ DE JUANA

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ABSTRACT

The writer interprets the diastrophic history of Northeastern Venezuela, incorporating some hitherto unpublished data, especially from Margarita and Cubagua.

The first dated orogenesis is post-Tithonian, pre-Cretaceous, although there are indications that this may not be the earliest. Absence of Hato Viejo-Carrizal sediments from southeastern Anzoategui and southern Monagas suggests a Jurassic land there, uplifted in early Mesozoic or pre-Mesozoic time. In Margarita island, pre-Laramide granites may represent a post-Tithonian, or even earlier, orogenesis.

Barranquin to Chimana time represents an epeirogenetic cycle, ended by the Guayuta transgression. Guayuta to Santa Anita time is another epeirogenetic cycle, during which the basin was gradually filled.

In Margarita, a thick conglomeratic Lower Eocene section contains pebbles of ultrabasic rocks exposed on the island; these conglomerates, as well as the ultrabasics, are presumably related to a pre-Lower Eocene (Laramide) orogenesis. It is still uncertain to what extent these movements affected the center of the Maturín basin.

Late Eocene or post-Eocene orogenesis is demonstrated in the Cubagua basin by angular unconformity between the Eocene and Oligo-Miocene or Miocene. In the Maturín basin, post-Cretaceous, pre-Merecure movements produced: in the north, emergence of lowlands with coastal swamps (Naricual coals); in the south, uplift of the northern edge of the Guiana shield with northward offlap of the Merecure.

Oligo-Miocene (Carapita-Santa Inés) sedimentation was essentially epeirogenetic, interrupted by synepeirogenetic uplifts of the northern lands, which produced the Santa Inés flysch facies appearing at successively younger horizons from west to east. In the south of the Maturín basin, the sea was transgressive southward.

In early Pliocene or pre-Pliocene time, the Maturín basin suffered a short but violent orogeny, which folded and faulted older beds and led to a general transgression of Pliocene brackish-water sediments.

Medial or Late Pliocene (Antillean) orogenesis produced folding and faulting, generally along pre-existing structural lines. There has been some post-Pliocene uplift but no true orogenesis. Frequent earthquakes indicate that the region is still unstable.

ACKNOWLEDGMENTS

The analysis presented in this paper is based on observations made by the writer while working for two private oil concerns, the Standard Oil Co. of Venezuela, and the Cía. Española de Petróleos, complemented by his own field work and information obtained as a consulting geologist for various departments of the Venezuelan Government.

The manuscript has been read by K. F. Dallmus, Assistant Chief Geologist of the Creole Petroleum Corp., Frances Charlton Rivero, professor of Historical Geology and Paleontology at the University of Caracas, and Dr. Víctor M. López, Director of the Servicio Técnico de Minería y Geología, Ministerio de Fomento, Caracas.

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INTRODUCTION

Northeastern Venezuela is defined in the present paper as an irregular quadrangle bounded on the west by a meridian passing through the town of Aragua de Barcelona, on the south by the course of the Orinoco River, and on the east and north by the Caribbean Sea. Trinidad, although it belongs to the same general pattern, is excluded.

The dominant structural feature of Northeastern Venezuela is a series of chains and depressions that strike about N.80° E. and extend in a parallel form, from the islands of Nueva Esparta in the Caribbean Sea to the Venezuelan Guiana highlands. These successive chains and depressions determine, from north to south, the following geologic provinces shown in Figure 1:

Margarita range
Cubagua depression
Araya-Paria coast range
Cariaco depression
Serranía del Interior (Interior ranges)
Maturín basin
Northern rim of the Guiana shield.

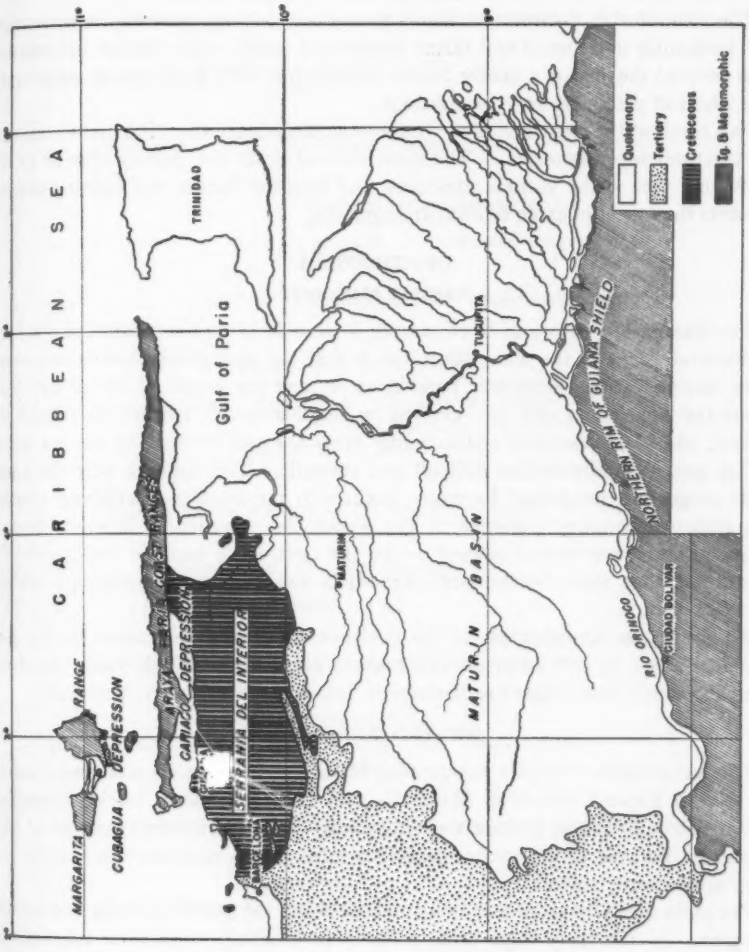

FIGURE 1.—*Geological provinces of Northeastern Venezuela*

The structural pattern of Eastern Venezuela is the result of a southward push from the hypothetic foreland of Paria against the stable Guiana complex, which produced a zone of high deformation close to the foreland and a zone of low deformation near the stable mass.

The zone of high deformation shows spectacular folding, generally asymmetrical and frequently overturned and thrust toward the south, while the low-deformation area adopted the form of a gently folded synclinorium with some lines of strike faulting, which at places are very conspicuous.

As a result of the repetition of the orogenetic movements there is a certain amount of structural superimposition. The main lines of uplift are slightly oblique to the individual axes of the various structures, and thus the folding and faulting pattern presents the aspect of an en echelon arrangement.

DIASTROPHISM

GENERAL STATEMENT

The diastrophic history of Northeastern Venezuela is very complex and not fully understood. One of the main difficulties is that the geologically best-known areas were, during various orogenetic periods, at or near the center of the geosyncline, where the movements were not reflected by long hiatuses or spectacular angular relations, while large portions of the border areas are now covered by the sea which makes geological observation difficult and sporadic. This explains why the Laramide orogenesis, recognized by many workers in the Antillean-Caribbean islands, has little confirmatory evidence in the Venezuelan mainland. The late Eocene or post-Eocene movements appear to be the controlling tectonic feature, chiefly because at that time Northeastern Venezuela was incorporated with the mobile northern belt.

By giving due consideration to the evidence of tectonic movements in the geosynclinal areas, as well as to the observations in the border-lands, Table 1 has been compiled which summarizes the diastrophic history of Northeastern Venezuela.

PRE-CRETACEOUS STAGES

The metamorphic complex outcropping in the Araya-Paria coastal ranges and in the Nueva Esparta islands of Margarita and Coche represents marine deposition during one or more long periods of epeirogenesis. This is almost all that can be said at present, because as yet not one problem related to the metamorphic complex has been satisfactorily solved.

The main difficulty is our lack of knowledge about the age of the rocks forming the complex. In the early days these rocks were generally considered Paleozoic as shown by the publications of Reinhard (1922), Liddle (1928), De Cizancourt and Schneegans (1936), but after Trechmann's (1935, p. 166–171) discovery of Cretaceous fossils in the Northern Range of Trinidad, there was a tendency to consider all the metamorphics as late Mesozoic. Therefore Kugler (1936, p. 1441) postulated a Cretaceous age for the sediments of the Northern Range of Trinidad, and Aguerrevere and Zuloaga (1937, p. 22) suggested a correlation of the metamorphic complex of North-Central Venezuela with well-established unmetamorphosed formations of Cretaceous age.

In 1938 Hutchison found a few specimens of *Perisphinctes transitorius* Zittel in the northern range of Trinidad, and subsequently Kugler's (1939) views were some-

TABLE 1.—*Diastrophic history of Northeastern Venezuela*

	Quaternary stage	Alluvium and Diluvium Mesa formation	
	Late Pliocene orogeny		
PLIOCENE EPEIROGENY		Cubagua basin: Araya fm.	Maturín basin: Sacacual group
	Early Pliocene orogeny—Sacacual transgression		
OLIGO-MIOCENE EPEIROGENY	Middle Cenozoic stage	Cubagua basin: Cubagua fm.; Mottled clays	Maturín basin: Sta. Inés fm. (Quiamare member); Carapita fm. (Capiricual member); Merecure fm.
	Late to post-Eocene orogeny—Emergence of Serranía del Interior		
EOCENE EPEIROGENY	Eocene stage	Cubagua basin: Punta Carnero group	Maturín basin: ?
	Cretaceous-Eocene orogeny—Emergence of lands		
CRETACEOUS EPEIROGENY	M. Cretaceous-Paleocene stage	Santa Anita fm.; San Antonio fm.; Querecual fm.	Guayuta group
	Guayuta transgression		
	Early Cretaceous stage	Chimana fm.; El Cantil fm.; Barranquín fm.	
	Post-Tithonian orogeny—Emergence of lands		
	Pre-Cretaceous stages—Araya-Paria metamorphic group		

what revised. Later Hedberg (1942, p. 202) expressed his opinion that the Coast Ranges of Northeastern Venezuela are at least Jurassic, and Wolcott (1943, p. 1632) found molluscan fossils east of Caracas, which are probably of Jurassic age.

While it would be useless, now, to enter into further controversial questions about the age of these rocks, the writer desires to express his opinion that whereas in Margarita some Cretaceous sediments were probably thermally metamorphosed, the bulk of the metamorphic complex, and especially the Araya-Paria metamorphic rocks, represent not only the Jurassic stage but possibly some older stages as well.

POST-TITHONIAN OROGENESIS

To explain the unconformable relationship between the metamorphic complex and the lowest unmetamorphosed sediments of the Barranquín formation, we must admit a post-Tithonian, pre-Urgonian period of orogenesis. Whether this post-Tithonian orogeny followed a more important medial-late Jurassic orogeny as suggested by Imlay (1943, p. 1519–1520), or various other Mesozoic and pre-Mesozoic orogenetic periods, cannot be proved yet, although it is probable.

Good indications of these early orogeneses are found on the island of Margarita by comparing the relative ages of the granitic intrusions of the Matasiete-El Tirano range and the ultrabasic intrusions so conspicuous in the rest of the island. The presence of rounded pebbles of basic igneous rocks in the lower Eocene conglomerates exposed at Moreno, on the eastern coast of Margarita, indicates that the ultrabasics are at least early Eocene, probably related to the Laramide orogenesis. As the granitic masses are unquestionably older than the peridotites, they in turn should be related to earlier orogenetic periods, either the post-Tithonian orogenesis defined above or some earlier revolution.

In southern Anzoátegui the Hato Viejo-Carrizal formation (Hedberg, 1942, p. 201) is missing toward the east where the younger Temblador formation rests unconformably on rocks of the Guiana complex. The relationship suggests that southeastern Anzoátegui and southern Monagas formed a dry land during the Hato Viejo-Carrizal deposition and that subsequently the Cretaceous Temblador seas transgressed southeastward on this part of the Guiana complex. If we accept the Jurassic age of the Hato Viejo-Carrizal formation, the corresponding Jurassic dry lands of southeastern Anzoátegui and southern Monagas were undoubtedly produced by some early Mesozoic or pre-Mesozoic orogenesis, whereas the Temblador transgression resulted from the late Jurassic orogeny.

The post-Tithonian, pre-Urgonian orogeny produced a land mass off the coast of Eastern Venezuela which was part of the hypothetical Paria borderland. The presence of Cretaceous in Margarita suggests that the lands which emerged near Venezuela were not a true borderland but a comparatively narrow geanticlinal ridge, perhaps only a festoon of islands, separating the Eastern Venezuela geosyncline from the northern Margarita seas.

CRETACEOUS EPEIROGENY

Early Cretaceous cycle.—The lithologic character of the lower sediments of the Barranquín formation gives some indication, albeit vague, about the nature of the southern coast of Paria. The moderate grain size of the sandstones indicates a coast line of low relief rather than abruptly rising mountains, and the lignitic clays and thin lignites show the existence of coastal swamps, a natural consequence of the low coastal relief.

The development of the lower-middle Cretaceous sediments is clearly cyclic. It begins with ferruginous sandstones, continues with predominantly reef limestones, and ends with sandstones again. Glauconite is common throughout.

The sequence of the three formations deposited during the lower-middle Cretaceous cycle (Barranquín, El Cantil, and Chimana) is well exposed at many localities, but the differentiation of the three is essentially arbitrary, since it depends upon the presence or absence of coral reefs. It is true that El Cantil is a strikingly thick reef formation, but there are also reefs in the Chimana and in the upper part of the Barranquín, which cannot be differentiated, either lithologically or paleontologically, from El Cantil. Furthermore, the transition from the Barranquín to El Cantil and from El Cantil to Chimana is very gradual, as shown by the following example: Well Monas No. 1, District Piar, State of Monagas, is one of the few wells which have drilled the Barranquín-El Cantil boundary. This test hole found the middle and lower El Cantil to be composed of about 35 per cent limestone, 36 per cent sandstone, and 29 per cent shale; the underlying upper Barranquín is composed of about 27 per cent limestone, 37 per cent sandstone and 36 per cent shale. Thus both formations are of similar composition.

Difficulties from the paleontologist's point of view are summarized by Hedberg and Pyre (1944, p. 10) in the following paragraph:

> "At the same time it is notable that pelecypods, gastropods, and corals from the lower part of the Chimana formation very closely resemble those from the upper part of the Barranquín formation."

Thus it appears highly questionable if these reefs mark true time-stratigraphic lines or even important changes in the sedimentary environment. Probably they represent mere recurrences of reef-forming conditions during the Venezuelan Urgonian cycle, which was essentially continuous and uninterrupted from the shoreline deposits of the lower Barranquín through the less clastic phase of El Cantil to the near-shore deposits of the Chimana formation.

Guayuta transgression.—The abrupt lithologic change from the uppermost Chimana to the lowermost Guayuta marks a widespread transgression of the Cretaceous seas called the Guayuta transgression. Whether the faunas of the Guayuta are called pelagic or planktonic they, as well as the type of sediments, are indicative of considerably deeper sedimentary environments.

The Chimana-Guayuta contact has been observed in many places, and an unconformity between the two formations has not yet been proved although it is suggested. The lithologic character of the contacting rock in the Chimana changes from place to place. In the islands of the Bahía de Pozuelo the contact is often characterized by whitish weathering, calcareous Querecual shales resting on reddish weathering sandy shales or on yellow-green glauconitic shales and glauconites of the Chimana. East of El Salto, a well-known part of the Neverí River, the Guayuta black shales rest conformably on a 5-foot bed of Chimana limestone bearing big ammonites, and slightly east of this locality, upstream in the same Neverí River near the mouth of Quebrada Pekín, the typical Guayuta calcareous shales rest on a bed of medium-grained, ferruginous, typical Chimana sandstone.

In the crest of the Bergantín anticline the lithologic change from Chimana to

Guayuta is very striking and strongly suggests an important transgression. Although the exact contact there is somewhat obscured by alluvium, in 1935 the writer found at, or very near, the base of the Guayuta, a thin conglomerate composed of black pebbles about three eighths of an inch in diameter; the significance of this has not yet been established.

Hedberg and Pyre (1944, p. 11) point out the possibility of a hiatus cutting out part, or all, of the Cenomanian Stage, but until further information comes to light we lack sufficient evidence to postulate an orogenetic period at the Chimana-Guayuta contact and prefer to consider that the Guayuta transgression was produced by a widespread synepeirogenetic[1] movement.

Middle Cretaceous-Paleocene cycle.—The Guayuta transgression was followed by a long period of epeirogenesis during which the Querecual, San Antonio, and Santa Anita formations were deposited. This sedimentary cycle, contrary to the lower-middle Cretaceous cyclic deposition, is characterized by a gradual filling of the basin which produced upward an increasing amount of sand deposition. Some lignites have been observed in the Santa Anita formation.

PRE-EOCENE OROGENESIS

Margarita-Cubagua area.—In the southern part of the island of Margarita there are exposed about 7500 feet of Eocene shales and sandy shales, coarse conglomerates, medium- to fine-grained sandstones, and flaggy orbitoidal limestones. The age of these sediments has been well established with the aid of the orbitoidal faunas.

The lower Eocene conglomerates, although widespread as a unit, are individually very lenticular; thick conglomeratic layers with pebbles reaching 2 inches in diameter grade, within a few feet, into sandstones and sandy shales. The pebbles found in the conglomerates are of heterogeneous materials, showing predominantly an assortment of all the hard older rocks exposed in the island—*i.e.*, metamorphosed dark-gray to green limestones, quartzites, and green ultrabasic rocks, as well as some vesicular extrusives which up to now have not been found *in situ* on Margarita.

The lower Eocene conglomerates of Margarita indicate emergence of lands of abrupt coastal relief at a time close to the Cretaceous-Eocene boundary, thus confirming previous observations about the extent and persistence of the Laramide orogenesis made at various places in the Antillean arch.

The presence of thick conglomerates and conglomeratic material stratigraphically higher indicates that uplift continued here during most of the Early Eocene period producing repeated coarse sedimentation. The ultrabasic intrusions of Margarita are probably related, or in some way associated with this orogeny, and volcanic activity probably also occurred at this time, although, as stated before, extrusive rocks have not been found *in situ* on Margarita.

Maturín basin.—The Cretaceous-Eocene orogenesis is more difficult to detect in the mountain belt of Anzoátegui and Monagas because this area was, at the time, near the center of the geosyncline. Another great difficulty arises from our still imperfect knowledge of the Santa Anita-Merecure contact.

The field investigations have not yet disclosed any significant unconformity be-

[1] Synepeirogenetic is used here to designate manifestations of orogenetic, or nearly orogenetic, character during typically epeirogenetic periods.

tween the formations, although at places the Santa Anita-Merecure contact suggests that the latter rests on an erosional surface.

The paleontological information available is very contradictory. Hedberg and Pyre (1944, p. 15) suggest the possibility that the Santa Anita may extend as high as upper Eocene and the base of the Merecure as low as upper Eocene thus precluding any significant hiatus between the formations; but other paleontologists (personal communications) restrict the Santa Anita to the uppermost Cretaceous and the Merecure to the uppermost Eocene or lower Oligocene, recognizing between both formations some sporadic thin Eocene remnants, the thicknesses of which increase eastward.

The Laramide orogenesis in the northern limb of the Maturín basin would, therefore, be explained in a different manner, depending upon which of these two opinions is correct. If Hedberg and Pyre's opinion proves to be true, then northeastern Anzoátegui was at the time too deep in the geosyncline to be affected by the movements of the Laramide orogenesis, which were only noticeable at or near the edges of the sedimentary basin. If, on the contrary, a significant hiatus exists between the Santa Anita proper and the as yet unnamed upper marly, algal, and shaly interval, this hiatus would reflect Cretaceous-Eocene orogenesis in the northern part of the Maturín basin.

EOCENE STAGE IN THE MARGARITA-CUBAGUA AREA

The conspicuously conglomeratic lower Eocene section of southern Margarita grades into sandstone, orbitoidal limestones, flaggy calcareous sandstones, and finally into dark-gray to chocolate-colored carbonaceous shales with a minor amount of thin, laminated, ferruginous sandstones, which mark the deepest subsidence of the sedimentary medium. Upward the shales grade into calcareous sandstones, flaggy orbitoidal limestones, and orbitoidal marls and sandy shales. Toward the close of the sedimentary cycle wave action on the previously deposited orbitoidal reefs, and redeposition in very shallow seas of the broken fragments, are noticeable west of the Punta Mosquito light house.

The Eocene sedimentary sequence appears to be unbroken by hiatuses or angular relations.

LATE TO POST EOCENE OROGENESIS

Cubagua basin.—At or near the end of the Eocene, lands in the Margarita belt emerged. Some of the newly deposited Eocene sediments were uplifted as evidenced by the exposures found west of Laguna de Las Maritas and near Zanjón Orinoco, in southern Margarita, where the Eocene is overlain with a strong angular unconformity by middle to upper Miocene sediments.

Some wells drilled in the island of Cubagua found about 4000 feet of Oligo-Miocene sediments unconformable on the Eocene, lithologically similar to the upper Eocene exposed at and near Punta Mosquito in southern Margarita. The lowest of these overlying sediments, generally considered Oligocene, are terrestrial mottled clays.

The best evidence obtained indicates that the late to post-Eocene orogenesis produced a dry land between the islands of Margarita and Coche, and possibly the main land of Araya, west of which the westward-sloping Cubagua basin was produced.

Maturín basin.—The appearance of the Merecure formation marks the beginning of a new sedimentary cycle which very soon became characterized by the terrigenous influence of dry lands. The Naricual coals extending from the mouth of the Unare River to the Amana Canyon, more than 80 miles along the strike[2], in places aggregate more than 50 feet of lignite and indicate very extensive paludal environments which from time to time suffered marine invasions. The great east-west extension of these coastal swamps points toward a slowly rising geanticlinal ridge of low relief which, in our opinion, was the incipient Serranía del Interior and which, before the deposition of the lignitic member of the Merecure formation, separated, at least partially, the Cubagua basin in the north from the Maturín basin in the south.

In the southern limb of the Maturín basin the waters regressed northward beyond the present location of the Oficina trend, as shown by many wells drilled in southern Monagas, Anzoátegui, and Guárico which found the Oligo-Miocene Oficina formation resting unconformably on the Cretaceous (González de Juana, 1944, p. 80).

The post-Cretaceous, pre-Merecure tectonic events in the Maturín basin may be summarized as follows:

1) In the north—emergence of low lands surrounded by extensive coastal swamps.

2) In the south—a general rising of the northern edge of the Guiana shield, with strong regression of waters toward the north.

Whether these changes were fundamentally produced by the Laramide orogenesis, by the late to post-Eocene orogenesis (Pyrenean phase), or by both will remain questionable until more information on the Santa Anita-Merecure relationship becomes available.

OLIGO-MIOCENE SYNEPEIROGENY

Cubagua basin.—The emerged lands between Margarita, Coche, and Araya produced in the eastern end of the Cubagua basin a typically terrestrial Oligocene(?) sedimentation characterized chiefly by mottled clays. Marine lower and middle Miocene deposits followed in the form of homogeneous, compact, silty, greenish-gray clay with streaks of claystone, overlain by a sandy section with thin streaks of fossiliferous, sandy, glauconitic limestone in the upper part.

The Miocene seas of the Cubagua basin were apparently transgressing eastward, covering first the lower regions of the irregular surface and flooding afterwards important portions of the Margarita-Coche land bridge, such as the southern coast of Margarita where the neritic, sandy limestones of the Cubagua formation (Dalton, 1912, p. 206) were deposited.

Maturín basin.—Following the Naricual swampy episode the Oligocene lowlands suffered a marine invasion. The waters gradually deepened during the time of deposition of the foraminiferal Carapita shale facies. Very soon, however, the incipient pre-Merecure ranges began to be uplifted and eroded, which resulted in a strong flysch deposition near the southern edge of the rising mountains.

Uplift of these ranges was not continuous and did not happen simultaneously in the various areas of northern Monagas and northern Anzoátegui. The first conglomerates, indicative of uplift and subsequent rapid erosion, appear south of Bar-

[2] The Altagracia de Orituco, Sabana Grande, *etc.* coals in the State of Guárico, about 60 miles southwest of the Unare outcrop, represent probably the same swampy episode of the Naricual member.

celona in the Capiricual member of the Santa Inés group (Carapita time) while the contemporaneous deposition of northeastern Anzoátegui and northern Monagas is characterized by a considerable thickness of marine shales. As time advanced the uplift extended eastward so that the conglomerates of the Santa Inés *sensu strictu* appear stratigraphically higher in the Quebrada Carapita, unconformable on the Carapita shales. This horizon closely corresponds with the time equivalent of the Capiricual-Quiamare contact defined by Hedberg and Pyre (1944, p. 23) in the Puerto La Cruz-Oficina highway.

Still farther east, in the Río Orégano, the first Santa Inés conglomerates and the corresponding angular unconformity between the Carapita shales and the Santa Inés formation *sensu strictu* occur at a still higher stratigraphic level. Thus the appearance of the Santa Inés flysch facies, which in every case marks the beginning of the rapid erosion subsequent to the uplift, does not follow a stratigraphic level but cuts across the time lines and is older in the west and younger toward the east.

In the northern Monagas, surface observations are rendered impossible because of the Pliocene-Quaternary cover, but the data obtained from petroleum drilling indicate that the tectonic process continued in a similar manner. As the Miocene seas receded southward, part of the Oligo-Miocene Monagas shale group (Regan, 1938, p. 188–189) was brought to the surface, and the La Pica shore line was produced. The sedimentation here is no longer conglomeratic, but medium to fine-grained sands predominate.

The upward movements of northwestern to north-central Anzoátegui, initiated during the Carapita, were repeated at different times during the Miocene; thus conglomeratic intervals such as El Pilar, Salomón member, and Dividive member, as well as local angular relations, were produced. These uplifts have been classified here as synepeirogenetic because we believe that Carapita-Santa Inés time was essentially an eperirogenetic period, but possibly further observation will disclose enough facts to classify some, if not all, of the Oligo-Miocene movements as truly orogenetic.

In the southern part of the Maturín basin, the Oligo-Miocene seas were transgressing southward lapping on the Cretaceous Temblador sediments (González de Juana, 1944, p. 80). During this process marine and swampy episodes were alternating as shown by the lignitic intervals of the Oficina formation.

EARLY PLIOCENE OROGENESIS

At the end of Miocene time the Maturin basin suffered a short but violent period of orogenesis which produced folding and faulting in older sediments.

The most outstanding feature of this early or pre-Pliocene revolution was a general transgression of the Sacacual-Las Piedras brackish sediments on every known formation from Miocene to Cretaceous. In northern Anzoátegui the Sacacual group shows an angular relation with the Dividive member of the Santa Inés formation at Orijuan; in the central Anzoátegui (Santa Ana-San Joaquín area) it rests unconformably on the upper Miocene Punche formation, and in northern Monagas overlaps from south to north the La Pica formation, the Monagas shale group, and various Cretaceous formations, including the El Cantil.

In the Cubagua basin a quartz gravel bed exposed in the north side of the island

of Cubagua, in the locality called Las Calderas, probably represents the Miocene-Pliocene break, but for the rest both formations appear to be conformable.

PLIOCENE EPEIROGENESIS

The Sacacual-Las Piedras sediments are brackish-water deposits composed of blue-gray to greenish-gray shales, laminated, lignitic sands, silts, and shales, lignites and thick medium-grained water sands. Manger (1932, p. 32) calls them "characteristic deltaic deposits," and they probably mark the first stages of the present Orinoco Delta.

In the Cubagua area the Pliocene deposits consist of brown, calcareous friable, fossiliferous sands and brown, sandy, fossiliferous clays of shallow marine origin.

LATE PLIOCENE OROGENESIS

After the deposition of the Sacacual-Las Piedras group, northeastern Venezuela suffered an extensive orogenesis corresponding to the Antillean Revolution (Medial Pliocene?) which is generally reported as the greatest orogenetic movement affecting the Caribbean-Antillean territory since the Paleozoic.

In the Maturín basin the Pliocene sediments were folded and faulted, generally along previously existing structural lines, and in the Cubagua basin the sediments were similarly affected by this orogeny as shown by the anticlinal folding and faulting of Cubagua and by the folding of southern Margarita and western Araya.

QUATERNARY STAGE

Following the Antillean Revolution the terrestrial Mesa deposits blanketed most of the Maturín basin. The topographic forms of Northeastern Venezuela were established, and a period of strong erosion set in.

Movements have recurred from time to time up to the Recent, as shown by the frequent earthquakes along the northern coast, which have elevated the Pleistocene mesas in the Maturín basin and some of the Pleistocene beaches along the coast and in the islands, but no true orogenetic movements can be proven.

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Apartado 1554, Caracas, Venezuela

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BLACK HAND SANDSTONE AND CONGLOMERATE IN OHIO

BY KARL VER STEEG

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ABSTRACT

The lower and middle Mississippian strata of Ohio, known as the Waverly series, consist of five formations, from older to younger: the Bedford shale, the Berea sandstone, the Sunbury shale, the Cuyahoga formation, and the Logan formation. They were laid down in the great shallow basin known as the Appalachian geosyncline. The floor of the basin rose and sank from time to time so that shore conditions with mud, sand, and conglomerate might prevail at any place, to be succeeded by deeper water and limestone formation. Sometimes it was dry, and again deltas spread across it. This resulted in a succession of deposits, varying in character as the condition surrounding their deposition changed.

The Black Hand sandstone and conglomerate member of the Cuyahoga formation of Ohio has been one of the perplexing problems of the Waverly series. This conglomeratic sandstone, correlated with the Big Injun sandstone of southeastern Ohio,

forms the scenic cliffs and deep gorges of Old Man's Cave, the Rock House, Ash Cave, Cantwell Cliff, Conkle's Hollow, and Cedar Falls, in the Hocking County region.

The conglomerate facies of this sandstone occurs in elongate masses, from Vinton County at the south into Richland and Ashland counties to the north, a distance of more than 100 miles. The individual conglomerate lobes trend slightly west of north. The character of the sediments, which are marine, and the dip of the bedding planes suggest deposition in shallow water in rather strong currents with scouring action. All the evidence indicates that the currents came from the south; the true bedding planes dip 3°–15° and range in direction from N. to NE. to E. to NW.

The pebbles of the conglomerate, which are quartz, are a quarter of an inch to more than 2 inches long. They are well rounded, indicating that they have been reworked several times. The source of this quartz is believed to be to the north and northeast. When traced horizontally from the conglomeratic masses, the Black Hand member thins and contains more shale, and the sandstones are finer and do not exhibit the strong cross-bedding and evidence of scouring action. The change in facies is accounted for by the explanation that the area, during the deposition of the Black Hand member, was a shallow interior sea in which bars, spits, beaches, and deltas were developed. What appears to be a bar was built on the west side of the area. Quiet lagoons were present in which finer sands and muds accumulated. The thickness of the Black Hand (Big Injun) conglomerate suggests that the area was sinking during the accumulation of the Black Hand conglomerates. The variation in thickness of the Black Hand and the irregular contour of its top suggest a disconformity with the Berne conglomerate member above, at the base of the Logan.

INTRODUCTION

L. E. Hicks (1878) described the deposits of coarse sandstone and conglomerate exposed at Black Hand in the gorge of the Licking River near Hanover, Ohio, as the Black Hand formation (conglomerate). Prosser (1901) reviewed the work of previous writers on the stratigraphy of the Waverly in Ohio and adopted the divisions made by Hicks and Herrick and gave them proper geographical names. In the classification of Prosser the Black Hand was considered a formation and included the Black Hand and Berne members of the Cuyahoga formation and the Byer and Allensville members in the Logan formation. Hyde (1915) and Holden (1942) consider the Black Hand sandstone and conglomerate as a member of the Cuyahoga formation.

The area under cover in eastern Ohio is no so well known as that in the outcrop area in the western portion. Field work in the area of outcrop and examination of the well records in Ohio have made it possible to determine the areal distribution and thickness of the Back Hand (Big Injun) member of the Cuyahoga formation. Two maps and a number of cross sections have been constructed. The writer, following Hyde and Holden, mapped the geographic locations of the facies of the Cuyahoga and Logan formations. For the sake of simplicity all names for facies are abandoned, and they are referred to as the conglomerate and shaly facies.

ACKNOWLEDGEMENTS

The well records used in obtaining the data for this paper came from the files of the Geological Survey of Ohio and the United States Geological Survey. The expenses involved in gathering field data were subsidized by a grant from a research fund established at the College of Wooster by Dr. Robert Wilson, President of the Standard Oil Company of Indiana.

FIGURE 1.—*Map showing important points mentioned in the text*

THE FACIES

GENERAL CONSIDERATIONS

Because the Black Hand member varies so much in composition within comparatively short horizontal distances, there has been considerable difficulty in tracing it. The thick masses of sandstone and conglomerate near Newark, Ohio, in the Hocking County area, not far from Logan, and in numerous other localities thin rather abruptly to dark shales or alternating thin beds of sandstone and shale.

Apparently the Black Hand member accumulated under variable conditions, such as prevail along a shore line where finer sands and muds were deposited in lagoons and in quiet, deeper waters offshore, or in bars, beaches, and deltas, where stronger currents may have prevailed.

Table 1 shows the relation of the Black Hand member to the other members of the Waverly series.

TOBOSO FACIES

The elongate mass of Black Hand sandstone and conglomerate, extending from Perry County to Ashland County, strikes about N. 10° W. (Fig. 3).

The Black Hand member outcrops near the surface in the northwest part of sec. 16, Milton Township, Ashland County, at an elevation of 1240 feet. Its thickness here is estimated at 80 to 90 feet. To the north the hills are lower, and the Black Hand member has been removed by erosion. In Montgomery Township, sec. 32, Ashland County, a well was drilled through soft, coarse-grained gray sandstone. Farther west, in Ashland County, the Black Hand member changes rather abruptly to the shaly, fine-grained sandstone facies.

Near Ontario, sec. 34, Springfield Township, Richland County, 15 feet of coarse, gray sandstone containing white quartz pebbles is exposed at an elevation of 1500 feet. This outcrop is near the western edge of the area underlain by the Black Hand member. At Pavonia, northeast of Mansfield, Richland County, in an old abandoned stone quarry is an excellent outcrop of the Black Hand member. About 60 feet of massive, coarse-grained yellowish-gray sandstone is exposed. It is highly conglomeratic at the base and near the top. One wall shows a massive conglomeratic sandstone, 30 feet thick, without a single bedding plane. About 20 feet above the base is a series of conglomerate lenses with white, quartz pebbles, from an eighth of an inch to an inch long. One pebble 2 inches long was observed by the writer. The bedding in the conglomerate lenses dips about 20°NW., indicating a strong current from the southeast when deposition took place.

In Mansfield, near the Prison Farm in Richland County, the Black Hand member is exposed in some large abandoned stone quarries. A massive, coarse-grained, yellowish-gray sandstone outcrops in cliffs 60 feet high. Pebbles are not abundant, but one finds small, white quartz specimens which are characteristic of the Black Hand member. The bedding planes in these quarries dip 5°–10°E.

In sec. 34, Mifflin Township, Richland County, about 6 miles east of Mansfield, a well record indicates a thickness of 190 feet of the Black Hand (Big Injun) sand. At the head of Possum Run, sec. 16, Washington Township, Richland County, about 30 feet of the Black Hand member is exposed, containing the characteristic white

TABLE 1.—*Formations, members, and facies of the Lower Mississippian rocks in Ohio*
Adapted from Hyde, Holden, and earlier workers.

LOGAN FORMATION

TABLE 1.—*Formations, members, and facies of the Lower Mississippian rocks in Ohio*
Adapted from Hyde, Holden, and earlier workers.

LOGAN FORMATION

Vanceburg sandstone facies	Scioto Valley shale facies	Pretty Run sandstone facies
Vinton sandstone member	Vinton sandstone member	Rushville shale member
		Vinton sandstone member
Churn Creek sandstone and shale member		Allensville Conglomerate member
Vanceburg sandstone member	Portsmouth shale member	Byer sandstone member
Rarden shale member		
Buena Vista sandstone member	Buena Vista sandstone member	Berne conglomerate member

CUYAHOGA FORMATION

Henley shale facies	Hocking Valley conglomerate facies	Granville shale facies	Toboso conglomerate facies	Killbuck shale facies	River Styx sandstone facies	Tinkers Creek shale facies	Big Injun conglomerate facies
	Black Hand conglomerate member	Black Hand sandstone member	Black Hand conglomerate member	Black Hand shale member	Black Hand sandstone member		Black Hand sandstone and conglomerate member
Henley shale member	Fairfield sandstone member	Raccoon shale member	Pleasant Valley shale and sandstone member	Armstrong sandstone member	Armstrong sandstone member		
	Lithopolis sandstone member			Burbank shale and sandstone member	Rittman conglomerate submember		
						Meadville shale member	
						Sharpsville sandstone member	Squaw sandstone and conglomerate member
						Orangeville shale member	
						Aurora sandstone submember	

SUNBURY FORMATION
BEREA FORMATION
BEDFORD FORMATION

quartz pebbles. A water well, in the western part of sec. 1, Perry Township, Richland County, passes through sandstone, 60 feet thick, believed to be the Black Hand. About 15 to 20 feet of soft, yellowish-gray, coarse-grained sandstone is exposed in an abandoned quarry, near Highway 97, between Bellville and Butler. In sec. 13, Jefferson Township, Richland County, on a hill toward the Clear Fork, the Black Hand

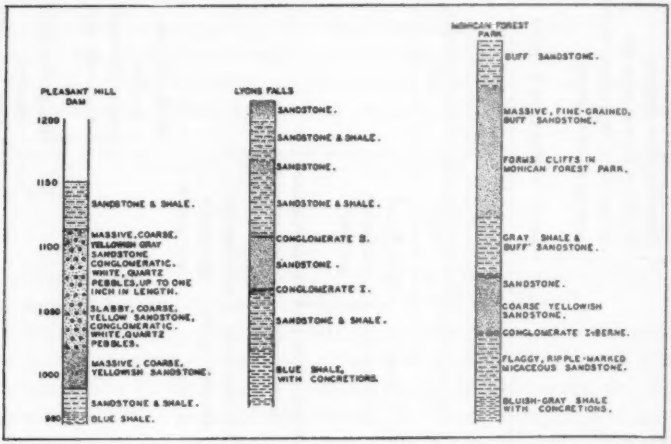

FIGURE 2.—*Sequence of strata at Pleasant Hill Dam, Lyons Falls, and Mohican Park*

member shows up to good advantage. The entire thickness, 60 feet, is present here. It contains white quartz pebbles throughout. The bedding planes dip W.

Along Switzer Creek, sec. 34, Monroe Township, Richland County, about 30 feet or more of the Black Hand is exposed. It is the typical yellowish gray, is coarse-grained, and contains white quartz pebbles. A well record in southeastern Monroe Township, Richland County, shows a thickness of 80 feet of the Black Hand member. To the south, in eastern Worthington Township, near Butler, in Richland County, well records indicate thicknesses of 35, 50, and 70 feet of the Black Hand member.

A series of stratigraphic sections from Hanover Township, Ashland County, are shown in Figure 2. In Mohican Forest Park, at the picnic grounds, the writer made a cross section along the wall of Clear Fork gorge, representing a thickness of 302 feet. The conspicuous, nearly vertical cliffs which form the rim rock of the gorge of the Clear Fork are responsible for the scenery of the park and are composed of massive sandstone, 102 feet thick, in the Logan formation. Below this is a thickness of sandstone, under which occurs a thin bed of conglomerate, made up of small white quartz pebbles, one-fourth to half an inch in diameter. This bed ranges in thickness from 6 inches to a foot. Its position in the section and its relation to the beds above and below indicate that it is what has been described as the Berne member of the Cuyahoga formation. This conglomerate lies about 50 feet above the level of Clear Fork Creek. The Black Hand member which begins immediately below the Berne conglomerate is in the main a flaggy, ripple-marked, micaceous sandstone,

beneath which lie the bluish-gray shales with concretions, so characteristic of the Cuyahoga formation. The section in Mohican Forest Park is similar to that in Wayne County, described by Conrey and called by Holden (1942, p. 34–36) the "Killbuck facies".

Herrick (1888, p. 97–130) describes the section at Lyons Falls (Fig. 2) in Ashland County as "a magnificent exposure near the western line of Ashland County", and representative of northern Ohio. Lyons Falls is about a mile northwest of Mohican Forest Park, not far from the Clear Fork. The section, which is from the south wall of the Clear Fork, resembles that at Mohican Forest Park; not all the horizons can be traced from one locality to the other. The thick massive sandstone, forming the cliffs at the picnic grounds in Mohican Forest Park, contains more shale at Lyons Falls, where the section is typical of the Killbuck facies.

At Pleasant Hill Dam, a short distance north of Lyons Falls, sec. 6, Ashland County, one can see a fine exposure of the Waverly. The section is almost entirely massive, coarse-grained, yellowish-gray sandstone. Much of it contains small, white quartz pebbles. This sandstone is well displayed in the cliff at the dam. Above it lie the flaggy sandstone and shale beds of the Logan formation. The section at Pleasant Hill Dam is similar to that in the vicinity of Toboso and Hanover, in Licking County, although the Black Hand member, here, is not so conglomeratic, and the pebbles are not so large.

The three sections, described above, all within a distance of only 2 miles, are used here (Fig. 3) to show what great changes take place, horizontally, in the Waverly beds within comparatively short distances. The massive conglomeratic sandstone at Pleasant Hill Dam changes rather abruptly to the bluish-gray shales at Lyons Falls, a short distance to the south. This sharp change is typical of the Black Hand member. Although no fossils are present in the sandstone beds at Pleasant Hill Dam, there can be little doubt that they are, in part, the Black Hand member, which at Mohican Forest Park and at Lyons Falls is a bluish-gray shale containing concretions.

Herrick (1888, p. 97–130) recognizes the remarkable variations in the Waverly beds and points out that one of the greatest sources of ambiguity in the reports of the geologists in Ohio grew out of the attempt to construe local thickenings of the conglomerates of the Waverly. These are explained tentatively, he states, as deposits at the mouths of rivers and are traced as narrow bands, extending northwestward from Licking County, through Knox and Richland counties.

One of the best exposures of the Black Hand sandstone is in the quarries of the Ayers Mineral Company, southeast of Millwood, on the picturesque Kokosing River, about 10¾ miles directly east of Mt. Vernon, in sec. 25, Union Township, Knox County. The Black Hand member here is a uniformly coarse-grained, slightly conglomeratic, loosely cemented sandstone. Its color varies from almost white to grayish white, gray, yellowish gray, yellow, red, and buff. Much of it is tinted by its limonite cement. The sandstone crumbles easily under pressure. Under binoculars this sandstone appears to be made up of angular grains of clear quartz of uniform size. In some instances, there appears to have been deposition from solution of quartz between the sand grains, and quartz crystals are abundant. Some of the beds

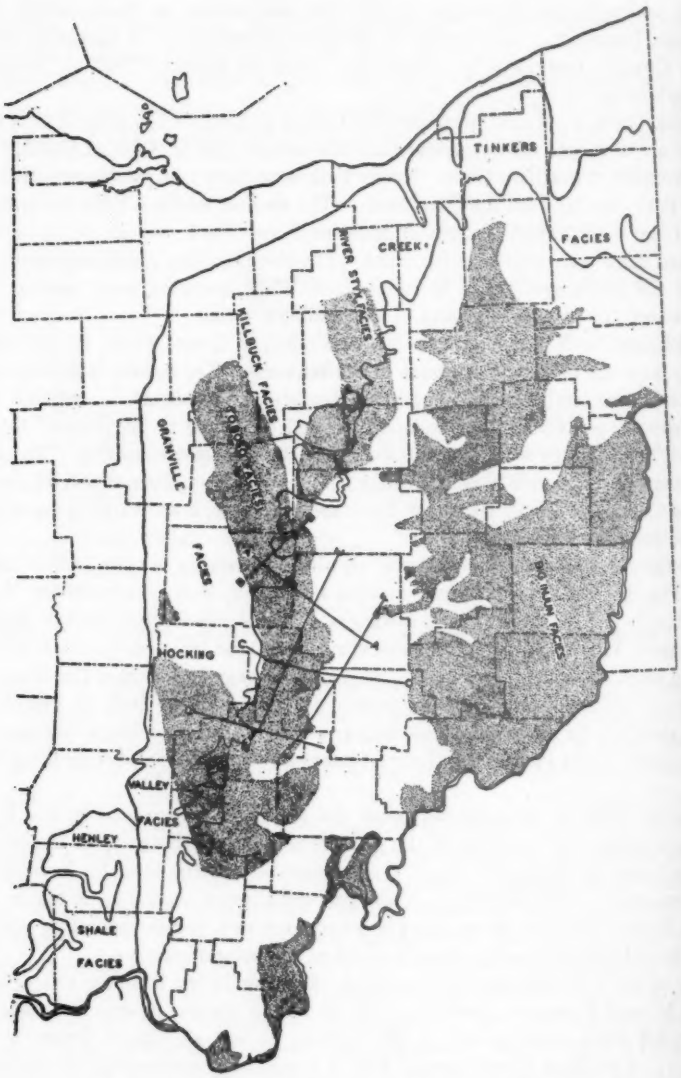

FIGURE 3.—*Map showing distribution of the various Black Hand facies and lines of cross section*

in the quarries are nearly white and are composed of clear grains of pure quartz; the sandstone is so pure that it is used for glass.

At Millwood, the Black Hand member is not so conglomeratic as at many places,

such as at Toboso and Hanover and in the Hocking County area, but it contains small, white quartz pebbles at some horizons. At the top of the quarry layer is a bed containing numerous white quartz pebbles, many of which are an inch or more in length. Some of the beds are as much as 3 feet or more thick, but most of them are from a few inches up to half a foot in thickness. It is flaggy and lenticular in places. The beds dip so slightly that they appear to be horizontal. Well-developed cross-bedding, a feature characteristic of the conglomerate facies of the Black Hand member, is absent here. From the meager evidence shown by the bedding in the Millwood quarries, it is difficult, if not impossible, to determine the direction of the currents which deposited the sand. The Black Hand member extends down to the Kokosing River for some distance above and below the Millwood Sand Plant, forming the cliffs of the picturesque Kokosing gorge, the walls of which stand 40 to 50 feet above the river.

In Liberty Township, Knox County, near Polk School and Weaver School, water wells penetrated the Black Hand sandstone. South of Bladensburg, sec. 24, Jackson Township, Knox County, near the iron bridge which crosses Wakatomika Creek, there is an outcrop of 40 to 50 feet of sandstone. A lenticular bed of coarse conglomerate, quite persistent and continuous, varying from a few inches up to half a foot in thickness, is exposed near the road level. The pebbles are white quartz from a quarter of an inch to as much as 2 inches in length. The sandstone above the conglomerate is coarse-grained and contains small pebbles. Below the conglomerate the beds are massive. There is cross-bedding and evidence of scour by strong currents during deposition. The bedding planes lie horizontally and do not indicate the direction of the current.

In section 20, Eden Township, Licking County, is the picturesque locality known as Rain Rocks. There is a fine exposure of the Black Hand member. An amphitheater-shaped hollow, an acre or two in extent, is partly surrounded by cliffs of the Black Hand sandstone. A cave 125 feet long, 40 feet deep, and 20 feet high has been hollowed out of the cliff by weathering and pothole action. The sandstone at Rain Rocks is red to yellowish inside but weathers to dark brown or deeper shades of red on the outside. The ledge is a solid mass of sandstone from base to rim. It shows all the characteristics typical of the Black Hand member, such as marked cross-bedding and evidence of scouring action when deposited, as indicated by long erosion surfaces which cut across bedding planes. The sandstone is conglomeratic throughout, containing white quartz pebbles, from an eighth of an inch up to an inch or more in length. The conglomerate is present in lenses and is not evenly distributed. The sandstone is coarse-grained and easily crushed. The cross-bedding dips in all directions. The well-developed, true bedding dips 5°–10°N. and NW. This prevailing trend of the dip of the beds indicates that the sand came from the south or southeast.

In an abandoned quarry on the hill about a mile south of Utica, Washington Township, Licking County, in an outcrop of the Black Hand member there is a massive, structureless cliff of sandstone, about 20 feet high, above which lies approximately 10 feet of slabby sandstone. The whole exposure differs from the typical Black Hand conglomerate facies in its general appearance. It is not coarse-grained and is

hard and very resistant to crushing. The buff-colored beds are horizontal and are not cross-bedded; no pebbles are present. Near the bottom of the cliff is a bed containing marine fossils. This outcrop occurs on the western edge of the conglomerate and sandstone facies, which may explain its character.

Along the Licking River, Hanover Township, Licking County, near the towns of Toboso, Hanover, and Claylick, and along the Black Hand Narrows, the Black Hand sandstone stands in high cliffs, making one of the most picturesque spots in Ohio. In the railroad cut, about half a mile from Toboso, a massive, almost structureless mass of conglomerate rises 40 feet above the road bed. Above this massive sandstone, up to the top of the cliff, there is 10 to 20 feet of horizontal, slabby, thin-bedded sandstone. There is a sharp line of demarcation between the two types of sandstone. The upper beds do not have the cross-bedding so typical of the conglomerate facies.

The Black Hand member in the Toboso and Hanover area can be described as a coarse-grained, easily pulverized, yellowish sandstone, containing white quartz pebbles, ranging from a quarter of an inch to as much as 2 inches in length; most are about half an inch to an inch in length. The sandstone contains more pebbles in some places than in others and appears to be lenticular. The cross-bedding is exceptionally well developed, occurs in all directions, and is independent of the true bedding, which has a definite direction and often shows well-defined ripple marks. The true bedding planes dip 9°–20°, the average being close to 10°, and strike N.10° W., or N.10°E.

At the abandoned Everts glass sand quarry, just beyond the railroad cut near Toboso, the vertical walls of the Black Hand member stand 60 to 65 feet high. The upper 20 feet is a thin-bedded slabby buff sandstone, finer-grained and horizontal. Below it is the coarse-grained, yellowish-gray conglomeratic sandstone, about 40 feet thick. This section shows excellent cross-bedding and true bedding planes displaying ripple marks. Many of the bedding planes are long erosion surfaces, extending for distances of as much as 30 yards. These show scour and erosion across the cross-bedding and are often undulating. Some of the bedding planes have thin shale horizons above them. Dips of 15°–20° are rare; an average of 10° in the direction N.10°–15° E. is nearly correct. The sandstone contains white quartz pebbles from a fourth of an inch to an inch in length.

Across the Licking River, opposite the railroad cut and the Everts sand quarry, there is a high cliff and lower bench of the Black Hand member, showing true bedding with well-defined ripple marks, dipping 10°–20° in the direction N.10°E. Many other outcrops of the Black Hand member in the vicinity of Toboso show dips of the bedding planes ranging from 5° to 15°, averaging about 10° in the direction N.10° E.

Along the road, on the north side of the Black Hand Narrows, between Toboso and Hanover, the cliffs of the Black Hand member rise to great height; in some places 80 to 100 feet is exposed. All the characteristics typical of the Black Hand conglomerate facies are shown here, such as the marked cross-bedding, the yellowish-gray color, and the numerous white quartz pebbles.

Westward from Toboso, on the road through the Black Hand Narrows, the dip of

the bedding planes is N.10°E., but farther down the road, in an easterly direction, at a point beyond the tunnel and about midway in the Narrows, the dip which is 5°-10°E. shifts to a N.10°–20°W. direction. Evidence of scour and erosion along the bedding planes is visible in a long line of exposures of the Black Hand member along the Black Hand Narrows at Licking River. Everywhere, in the Narrows and in the vicinity of Toboso, Hanover, and Claylick, the Black Hand shows well-developed cross-bedding in all directions, with the true bedding planes inclined at an average angle of about 10°, slightly to the east or west of north. About midway in the Narrows at the tunnel, the direction of dip shifts from NE. to NW. The difference in the inclination of the bedding planes on the east and west sides of the area, within a short distance, suggests that the conglomerate mass is not one of great horizontal extent and that the more easterly outcrops are really on the eastern side of the conglomerate area. To the east the Black Hand conglomerate facies goes under cover with all its characteristic structures present, but on the western side of the conglomerate area the bedding flattens out, and the current structures and cross-bedding disappear, together with the quartz pebbles, so that within a mile or two the Black Hand member becomes a structureless sandstone. At Claylick, 2½ miles west of where the structures are shown at their maximum development, thin beds of shale begin to appear below the massive upper 100 feet of the Black Hand member. This change suggests that the Granville shale facies is being approached.

HOCKING VALLEY FACIES

Due to the eastward dip of the formations the Hocking Valley exposures of the Black Hand member can be studied more thoroughly, since this member lies far enough west on the outcrop belt so that more of the structure is exposed. The Toboso-Hanover area lies so far east that only the upper 100 feet of the Black Hand can be observed, and we must rely on well records to get the data.

The Black Hand occupies the central and western portions of Fairfield and the western half of Hocking counties, extending to the northern border of Vinton County. The Black Hand member is also exposed in the southwestern part of Licking and the western margin of Franklin counties. The outcrop, along its western margin, is about 50 miles long, and its greatest width is about 20 miles. Due to the prevailing dip of the beds, only the upper portion of the Black Hand is exposed in the eastern and southeastern portions of the outcrop, whereas in the western part only the lower portion remains. At few places is the entire thickness of the Black Hand member exposed. Well records are valuable as an aid in determining the structure. The Black Hand conglomerate facies is developed along an axis trending about N.20°W.

In the Hocking Valley area, the Black Hand sandstone is the most important cliff-forming member of the Cuyahoga formation; the outstanding scenery of Fairfield and Hocking counties is mainly the result of the erosion of this resistant, conglomeratic sandstone. The thickness ranges from 100 to 400 feet, near the center of the province.

The Black Hand member extends laterally beyond the lower members of the Cuyahoga formation and continues to the eastern part of Fairfield County, where it disappears beneath cover, with complete loss of structural features, except for the

horizontal bedding and the shales below it, as reported from well records. It caps the hills almost as far west as Amanda and Tarleton. West of that line, it has been removed by erosion. It appears at a point not more than 3 or 4 miles north of Lancaster.

The outcrop of the Black Hand can be traced without difficulty in the southwest corner of Hocking County, and the northeast corner of Ross County, and its transition westward from sandstone into the shales of the Cuyahoga formation can be determined. Throughout the central portion of the Fairfield-Hocking counties province, the Black Hand is a coarse, yellowish, pebbly sandstone, with occasional lenses of conglomerate. The pebbles of milky white quartz average from a quarter to half an inch in length and seldom exceed an inch. Occasional pebbles are 2 inches in length.

One of the striking features of the Black Hand member, as in the Toboso-Hanover area, is the bedding which is inclined 5°–15°. Readings on bedding planes that show ripple marks and other features of true bedding give an average inclination of less than 10°. The writer observed no angles greater than 15°, and this inclination is rather unusual. Dips of 10° are most common. The direction of dip is most prominent on the eastern side of the area and is more frequently to the northeast. Dips in the direction of N.30°–40°E. are common. Inclinations to the north and northwest are also present. One is impressed by the general northerly dip of the bedding planes, as found throughout the Black Hand member. One of the marked features of the Black Hand conglomerate are the well-developed erosion surfaces along the bedding planes. These indicate scour by currents of considerable velocity in shallow water.

The Black Hand member is not found more than 3 or 4 miles north of Lancaster; the hills beyond that point have lower altitudes. Along the road, north of Lancaster, about 15 feet of the Black Hand is exposed. The bedding planes dip about 5°E. On the south side of Lancaster, in a large sandstone quarry, the massive Black Hand member is well exposed in a cliff 80 feet high. The base is not exposed in the quarry or in the bed of the Hocking River, close at hand. White quartz pebbles are present but not in large number. The bedding planes dip 3°–5°E. North of Lancaster, the Black Hand is exposed at Mt. Pleasant where it forms a spectacular cliff. In the vicinity of Lancaster, the Black Hand is thick; it thins to the east where it disappears under cover. Here it loses the typical character of the conglomerate facies and exhibits the shaly Granville facies.

Near Sugargrove and along the highway to Rockbridge in Hocking County, in numerous outcrops of the Black Hand the bedding planes dip 2°–7°E. and NE. In the Hocking County Forest Park area, in Laurel and Benton townships, the Black Hand member forms prominent cliffs along the streams which have cut deeply into it, forming narrow, steep-sided gorges, the walls of which are usually vertical or overhanging. The scenery of the park area is almost entirely the result of the erosion and weathering of the Black Hand sandstone. At Cantwell Cliff, a narrow, vertical-walled gorge, the Black Hand member is quite conglomeratic, showing white quartz pebbles, averaging about half an inch with occasional ones an inch long. Cross-bedding in all directions is common. The bedding planes show evidence of erosion

FIGURE 1. EXPOSURE OF BLACK HAND MEMBER IN HOCKING VALLEY FOREST PARK AREA

FIGURE 2. CONGLOMERATIC SANDSTONE FACIES AT LOWER FALLS NEAR OLD MAN'S CAVE

TYPICAL EXPOSURES OF BLACK HAND MEMBER

and dip about 8°NW. Where the sandstone is softer or where pothole action has taken place, there are caves and coves of considerable size. At Cantwell Cliff the measured thickness of the Black Hand member is about 205 feet. About 4 miles from Rock House, on Highway 374, the Black Hand shows bedding planes dipping 5°–10°NE. The Rock House, a unique geological attraction, is a cave 200 to 225 feet long and 25 to 30 feet wide at the floor level. The Black Hand member has been weathered along the joints, forming a long corridor, opening out at the end in two gothic doorways, at a point about half the height of the cliff. Along its front, enlargement of the joints by weathering has produced large sandstone pillars; the portals between them serve as windows. There are five pillars and seven openings; each window is located along a large joint where weathering has been most effective. One set of vertical joints extends at right angles to the face of the cliff, and another set extends at right angles to the above-mentioned set and runs parallel to the face of the cliff. Enlargement by weathering along one of the major joints is responsible for the elongate corridor. The windows at the ends are located along the master joint. The Rock House is the product of differential weathering along two sets of master joints, running at nearly right angles to each other. At the Rock House, the bedding planes in the Black Hand member dip northwest from 5° to 10°, averaging 8°. Cross-bedding and erosion surfaces along the bedding planes are well developed. The Black Hand member, here, contains white quartz pebbles from an eighth to half an inch long. The measured thickness of the Black Hand is approximately 100 feet at the Rock House.

At Old Man's Cave, which is the most popular of the Hocking County parks, the Black Hand member forms the towering walls of a gorge more than 100 feet deep. The variable resistance of the massive beds to weathering and erosion has resulted in the formation of Old Man's Cave and the Lower Falls, near by, one of the most beautiful spots in Ohio. The Black Hand sandstone, here, contains white quartz pebbles. The bedding planes dip about 3°–5° to the north or slightly to the east of north. The direction of dip of the bedding planes shifts to the northwest as one proceeds up the gorge; it is 8°–10°NE. a short distance upstream. Evidence of erosion along bedding planes is common. The bottom of the Black Hand member can be seen in the cave at the Lower Falls. The contact with the gray and bluish-gray Cuyahoga shale below is undulating but does not appear to be an unconformity. The contact surface dips about 5° east of north. The writer obtained a thickness of about 115 feet for the Black Hand member at Old Man's Cave.

At Conkle's Hollow, the Black Hand is exposed in spectacular vertical and overhanging cliffs. The gorge which is not more than 300 feet wide ends in a semicircular cove which is the result of pothole action. The Black Hand sandstone is 150 to 200 feet thick. It exhibits the same characteristics found in other localities within the conglomerate facies area, such as white quartz pebbles, well-developed cross-bedding, and evidence of erosion along bedding planes. On the highway, just out of Conkle's Hollow, the Black Hand member shows dips of 5°–10° NW. along bedding planes. Here, the contact of the Black Hand with the Berne member above and the Logan formation below is exposed. The Berne and Logan are horizontal. The contacts appear to be irregular, suggesting an unconformable relation.

In the gorge, which ends in an overhanging ledge called Cedar Falls, the Black Hand member stands in vertical cliffs about 50 to 60 feet high. The base is not exposed. The bedding planes dip about 10°E. A few undulating, ripple-marked bedding planes, dipping about 15°NE., show the effects of scour. At the stone bridge on the highway at Cedar Falls, the contact of the Berne member with the Black Hand member and the Logan formation is exposed. These contacts appear to be irregular, suggesting an unconformable relation above and below.

Ash Cave is one of the scenic localities in Ohio. The ravine or gorge is narrow and deep and ends in a gigantic, semicircular cavern about 700 feet long, 100 feet wide, and 90 feet high. The projecting ledge of Black Hand sandstone, which forms the roof of the cave, is more resistant to weathering than the sandstone and conglomerate strata beneath. In the walls of the cave, the massive beds of the Black Hand show bedding planes with ripple marks. They dip 10° in a N.15°W. direction and show the effects of erosion during deposition. The base of the Black Hand is not exposed at Ash Cave. The portion of the member forming the cliff is estimated to be 80-100 feet thick.

There is a marked change in scenery as one proceeds westward from Ash Cave toward Haynes; the high cliffs and rugged topography of the area underlain by the Black Hand conglomerate change to the low, rounded hills of shale which are especially conspicuous beyond Haynes, east of Laurelville. The Hocking Valley conglomerate facies changes abruptly to the more shaly beds of the Scioto Valley shale facies as one proceeds westward. Horizontal bluish-gray shale beds, alternating with thin beds of fine-grained buff sandstone, make up the Scioto Valley shale facies. The rather sharp change, from the rugged topography in the area of the Black Hand conglomerate in the Hocking County park region to the more subdued features of the area underlain by the Scioto Valley facies, is very conspicuous. The outcrop of the Black Hand member, representing the Hocking Valley conglomerate facies, is sharply defined and indicates different sediments from those to the east and west which were laid down under different conditions of deposition.

Southwest of Lancaster, Fairfield County, well records indicate a thickness of 195 feet for the Black Hand member. In Benton Township, Hocking County, within the park area, well records show thicknesses of 175, 353, 294, 116, and 250 feet. Southwest of Logan, Falls Township, well records indicate thicknesses of 265, 300, 219, 200, and 222 feet for the Black Hand. North of Logan, along Hocking River, ripple-marked bedding planes show dips of 10°–15° in a N.30°–40°E. direction. About 2 miles northwest of Logan, the contact with the Berne member is exposed. The lower Berne, known as Conglomerate I by earlier writers, appears as a solid mass of white quartz pebbles in a bed 1 to 2 feet thick. It rests on an irregular surface. The contact with the Black Hand member is sharp and appears to be an unconformity. In this outcrop, from the road level to the top of the hill, one can see the top of the Black Hand, the Berne, and the Logan contacts. The top of the Berne makes an irregular contact with the Logan formation. The Berne member, at this point, is conglomeratic at the base with sandstone and shale beds; the latter increase toward the top.

The Berne member of the Logan formation lies immediately above the Black Hand member. It is a basal conglomerate composed of coarse, milky white quartz

pebbles and coarse quartz sand. In places, finer-grained sandstone and shale beds are present. Its thickness ranges from a few inches up to 15 feet; its average thickness is approximately 1 to 3 feet. The Berne rests on the uneven surface of the Black Hand member. When traced across the area where it overlies the Toboso-Hanover conglomerate facies, its altitude increases; it thins where the conglomerate thickness. The Berne is thickest where it overlies the thinner shale facies of the Cuyahoga and thinnest where it lies above the thicker conglomerate facies. The thickness of the Berne and the Byer members suggests that at the time of their deposition the Cuyahoga conglomerate areas were higher points between the areas of Cuyahoga shale. The sands and gravels accumulated to a greater thickness in the low areas over the Cuyahoga shale. The irregular surface of the Black Hand member doubtless increases the complexity. The white quartz pebbles of the Berne are to all appearances similar to those in the Black Hand. Apparently the erosive and carrying power of the currents washed the coarse gravel over and beyond the conglomerate masses and into the lagoons and quieter waters offshore, where the thinner and finer-grained sands and muds were accumulating.

Farther northeast, between Logan and Enterprise, the Black Hand shows bedding planes which dip 5°–10° in a N.40°E. direction. Northeast of Sugargrove, on the highway, about a mile west of Clark Crossing, a ledge of Black Hand, well up on the hillside, shows bedding planes dipping 5° in a N.50°E. direction. Along Rush Creek valley, in Marion Township, Hocking County, in an easterly direction, the upper part of the Black Hand is exposed at numerous places and disappears under cover in the eastern part of Marion Township, where it merges into the Granville shale facies. The dip of the bedding planes is about 5° in a 30°–40°E. direction.

GRANVILLE SHALE FACIES

In the abandoned Havens quarry, about 1½ miles southeast of the central part of Newark, is an outcrop of the Black Hand member—an exposure of what was called Conglomerate 1 by Herrick (1888, p. 107) and Prosser (1901, p. 220) and considered by them as part of the Black Hand formation. Hyde (1915, p. 657), in a revision of classification, placed Conglomerate 1 immediately above the Black Hand member, as the uppermost member of the Cuyahoga formation, and called it the Berne member. Conrey (1921, p. 49) and Holden (1942, p. 41) place the Berne member at the base of the Logan formation. In the section at the Havens quarry, Prosser describes Conglomerate 1 as a bed 3 feet thick, with a sandstone parting and composed of large pebbles. Where the present writer observed the outcrop, it appeared to be about 1 to 1½ feet in thickness, containing white quartz pebbles. The upper and lower surfaces of the conglomerate bed are very irregular and undulating; the bed thickens and thins and almost pinches out in places. Below it are the shales of the Black Hand member. This outcrop represents a shaly phase of the Black Hand, called by Hyde the "Granville shale facies". Here, again, we have an instance of an abrupt change from the shallow-water conglomerate facies to the deeper, quiet-water shale facies.

Farther west, at a point known as the "Dugway", near the junction of highways 16 and 512, about 1½ miles west of Newark and 4 miles from Granville, there is a

good exposure of the Black Hand member. It is composed, for the most part, of thin-bedded sandstones and shales. No cross-bedding is present, and the beds are horizontal. No conglomerate, so characteristic of the conglomerate facies not far to the east, is present.

In the Rose quarry, on the Denison University campus, there is an outcrop of sandstone and shale, mainly sandstone, which represents the Granville shaly facies of the Black Hand member. No white quartz pebbles are present, the sandstone is finer-grained than that of the Toboso-Hanover conglomerate, the beds are horizontal, and there is no cross-bedding. The Black Hand siltstone is exposed in the east-central part of the facies in eastern Granville and Newark townships, Licking County.

BIG INJUN FACIES

The Big Injun sand, widely known to the driller in eastern Ohio and northern West Virginia, is correlative with the Black Hand conglomerate which outcrops so prominently in Licking, Fairfield, and Hocking counties. It is massive, coarse, and often pebbly; where typically developed, it is an open, porous, coarse-grained, conglomeratic sandstone. Like its equivalent, the Black Hand member, it is generally cross-bedded and contains well-worn, white quartz pebbles which have a lenticular arrangement. It is invariably recognized by the driller, because of its coarse conglomeratic texture and the large flows of salt water which are encountered in passing through it. The cementing material is iron oxide, and the sandstone usually is buff. In some places, the bed is broken by layers of shale and shaly sandstone, which act as barriers to the circulation of oil, gas, and water.

The Big Injun ranges in thickness from less than 50 feet to more than 300 feet. The changes in thickness are rapid and abrupt in some places. It is widespread in its occurrence and is persistent over wide areas in Belmont, Monroe, Washington, Noble, Guernsey, Morgan, Muskingum, Vinton, Athens, and other counties in eastern Ohio. At a few localities in Ohio, where it is quite porous, it acts as a reservoir for petroleum and, particularly, natural gas. It is of most importance, economically, in Washington and Monroe counties and is of less value in Athens, Vinton, Morgan, Muskingum, Noble, Guernsey, and Belmont counties, where finer sands and the more shaly facies predominante. Where the sand is coarse the flow of gas is rapid. The Big Injun is often charged with water; the flow occurs near the base of the member. At Pomeroy, Meigs County, the Big Injun is the source of brine. In the past, the brines were used extensively along the Hocking River and along the Muskingum River in southern Muskingum and northern Morgan counties. Where the Big Injun is thinner, the fine-grained sandstones and shales predominate; oil and gas are absent.

When detached from the main body, the lower portion of the Big Injun is called the Squaw sand. In southeastern Ohio, the driller recognizes the Squaw sand not far below the base of the Big Injun. The Squaw sand lies in the upper part of the Cuyahoga formation and in this area appears to be correlative with the Sharpsville sandstone of Pennsylvania. In Columbiana County, the Squaw sand is separated from the Big Injun by nearly 50 feet of shale. The Squaw sand is usually coarse and in some parts is conglomeratic.

HENLEY SHALE FACIES

This shale member of the Cuyahoga formation, named from Henley, Scioto County, consists of alternating gray and red shales. The red color disappears to the eastward, together with the sandstones of the facies. There is considerable variation in the thickness of this shale. It is thinnest along its western outcrop zone in western Scioto, Pike, Ross, and eastern Adams counties and thickens northeastward from 5½ feet to 200 feet in east-central Pike County. No unconformity exists between the Henley shale and the underlying Sunbury shale.

STRUCTURE OF THE BLACK HAND MEMBER

Several cross sections, based on well records and field observations (Fig. 4), give a general notion as to the structure of the Black Hand member. Section AA, about 40 miles long, extends through eastern Licking and into Muskingum counties, across the Toboso-Hanover facies of the Black Hand. From northwest to southeast along the line of cross section, through the Newark and Frazeysburg quadrangles, the maximum thickness of the Black Hand member is 385 feet, and the minimum 20 feet. The average thickness through the Newark and Frazeysburg quadrangles, to a point about 7 miles northwest of Zanesville, is approximately 220 feet. This figure is based on 38 well records. Beyond this point, in the Zanesville and Philo quadrangles, the Black Hand thins abruptly, averaging only 55 feet. The Black Hand is not only thinner, but it becomes shaly.

Cross section AA shows that the surface of the Black Hand member makes a broad arch about 10 miles wide, sloping gradually to the east and more abruptly to the west. The conglomerate mass is somewhat lens-shaped, thinning down sharply to the east.

Section BB extends northeasterly from a point near Newark, cutting across the northwestern corner of the Frazeysburg quadrangle near Fallsburg, ending near the southern border of the Brinkhaven quadrangle. The thickness of the Black Hand member along this section ranges from a minimum of 110 feet to a maximum of 380 feet; the average thickness at 35 locations along the line of the section is 263 feet. This section, which is 22 miles long, cuts across the conglomerate facies of the Black Hand member; the top shows the contour of a broad arch.

Section CC extends through the Thornville, Zanesville, New Lexington, and into the McConnellsville quadrangles, a distance of about 40 miles. From west to east, for 20 miles, the thickness of the Black Hand member varies from 80 to 300 feet; the average for 17 well records is 203 feet. The thickness changes abruptly in York Township, Morgan County, from 235 feet to an average of only 39 feet; 20 to 30 feet is common for the next 20 miles and beyond. The sharp change in thickness is accompanied by a change in the character of the sediments; the conglomerate changes to more shale and finer-grained sandstones to the east. The top of section CC shows the contour of a broad arch, but the bottom is concave, as one might expect of materials laid down in a trough. An eastward continuation of section CC shows an abrupt thickening of the Big Injun sandstone. From the thin shaly facies of northern Morgan County (35 to 59 feet), the coarser sand and conglomerate reaches thicknesses of 100 to 300 feet in Noble and Monroe counties.

Section DD extends from a point about 4 miles east of Amanda, Fairfield County, about 2 miles south of Sugargrove into Hocking County, and eastward into Athens County near Glouster, a total distance of about 36 miles. The Black Hand member is slightly over 100 feet thick in the area crossed by section DD, in Lancaster, Logan,

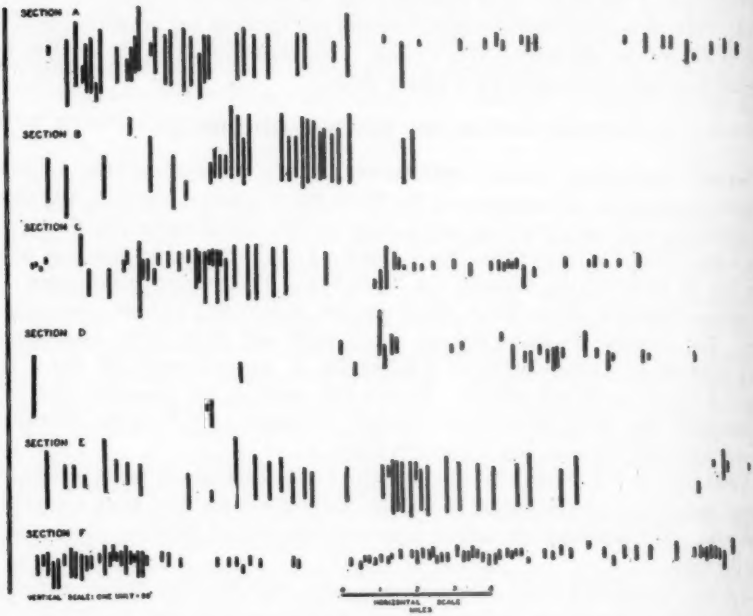

FIGURE 4.—*Series of cross sections along lines indicated on map* (Fig.3)
Constructed from data obtained from the files of U.S.G.S.

and New Lexington quadrangles. Farther east, the Black Hand member is somewhat thinner, until in the vicinity of Glouster it is only 25 feet thick. To the east the conglomerate facies of the Black Hand member passes to a shaly type of sediment. Section DD shows the archlike contour of the top of the Black Hand and a concave outline along its lower margin.

Section EE extends for 41 miles to the northeast, from a point south of Logan in Hocking County, to Dresden in Muskingum County. This section shows the abrupt change in thickness as one passes from the conglomerate facies of the Black Hand to the sandstone-shale facies. For 30 miles, through the conglomerate facies, the thickness of the Black Hand ranges from 30 to 400 feet; the average for 37 well records is 198 feet. Where the conglomerate facies ends and the shaly facies begins, near Hopewell in Muskingum County, the Black Hand member averages only 60 feet or less.

Section FF, for a distance of 40 miles, trends northeast from a point in northeastern Hocking County across eastern Perry County, through Muskingum County, to a point beyond Norwich in Union Township, Muskingum County. Numerous well

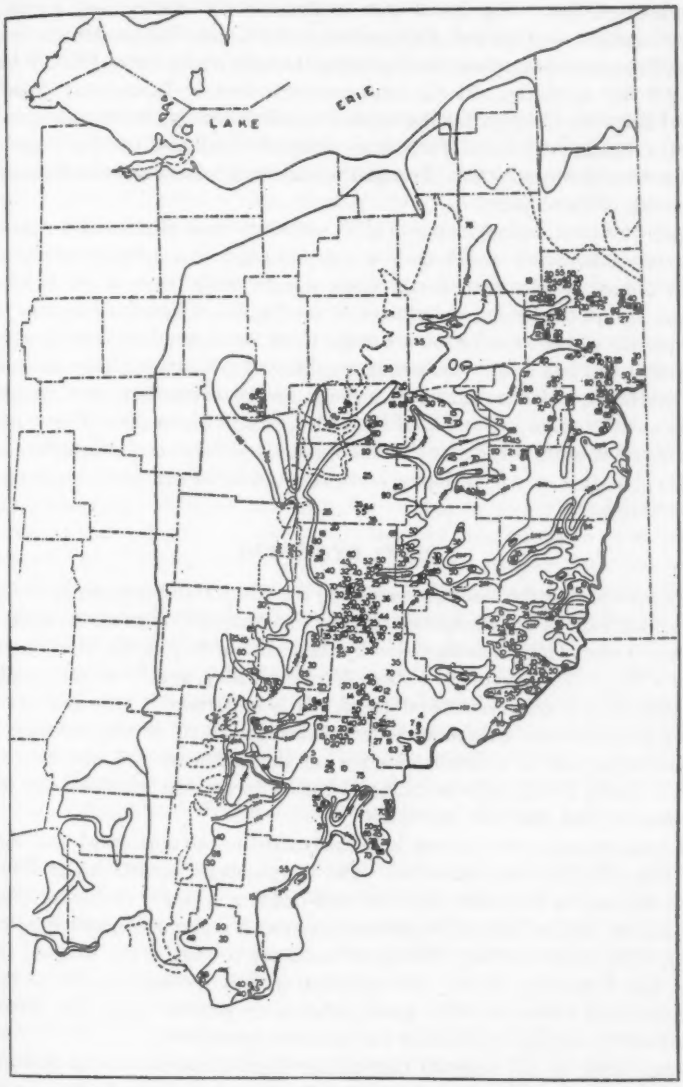

FIGURE 5.—*Isopach map, showing thickness of the Black Hand member*
All thicknesses less than 100 feet are indicated by figures.

records indicate the average thickness of the Black Hand, for a distance of 6 miles in a northeasterly direction in Hocking County, to be about 92 feet. From there, northeastward, it thins abruptly, and the average for the remaining 34 miles along

the section is 43 feet. The line of cross section is in the thinner shaly facies. Farther northeast, beyond the end of the section, in the Cambridge quadrangle in Guernsey and Tuscarawas counties, the Big Injun thickens markedly to 100–150 feet and up to 250 feet in places. In the southwestern corner of Tuscarawas County and adjacent Guernsey County, the Big Injun is a well-defined layer, ranging from 125 to 295 feet, averaging 165 feet. There is an abrupt thickening of the Big Injun, east of a line running north and south, through the Cambridge quadrangle, at a point about 3 miles west of Cambridge.

As indicated on the isopach map (Fig. 5), any of the cross sections and others which might extend eastward would show a sharp change, in passing from the thicker western Toboso conglomerate facies to the thinner shaly facies to the east, beyond which an abrupt thickening and change to the Big Injun facies takes place.

The present elevation and structure of the Black Hand member is not the same as it was when it was laid down. Subsequent uplift and deformation have given it a dip to the southeast, which is the present regional direction of inclination of the sedimentary rocks of the area. The dip of the beds averages about 25 to 30 feet per mile. The evidence appears to indicate that the Black Hand member was deposited in early Mississippian time, on a floor sloping northward out to the sea, which lay to the north and northwest.

DELTA HYPOTHESIS

The evidence that the material composing the Black Hand member in the Toboso and Hocking Valley conglomerate masses was transported by currents from the south-southeast is abundantly substantiated by data obtained by Hyde, Holden, and the present writer. The axes of the Toboso, Hocking Valley, and River Styx conglomerate masses have a north-northwest trend. It is important to note that the dip of bedding planes in each conglomerate facies averages 5°–10° to the northeast, north, and northwest, and is somewhat steeper on the northeast and east flanks of the masses. Owing to the regional tilting to the southeast, the westward dips are less than those to the east and northeast.

The conglomerate facies narrow in lateral extent to the northward, and the shale facies widen in the same direction. The conglomerate masses merge into finer-grained deposits to the north, and the cross-bedding is poorly developed or absent. In the eastern area, where the Black Hand member is under cover, well samples from the Big Injun facies indicate lithological similarity to that of the Toboso, Hocking Valley, and River Styx facies. The lenticular masses of conglomerate, composed of coarse sand and well-worn white quartz pebbles, are present here. The direction of the currents in the Big Injun facies has not been determined.

Holden (1942, p. 65) suggests that strong shore currents or wave action would spread the sand and gravel deposits laterally alongshore from the long axes of the facies. Under such conditions the conglomerate facies would not have formed the distinct lobes so sharply defined from the shale facies. The rather abrupt change from one facies to the other, and the presence of numerous instances of irregular cut and fill type of cross-bedding in the conglomerates and sandstones suggest deposition under the influence of strong currents at or near river mouths.

Evidence suggests that there were protected areas, where more steeply dipping conglomerates were deposited. Where cross-bedding is poorly developed or absent, stream currents were probably unimportant, and shore and wave currents predominated.

The conglomerates could be interpreted as nonmarine gravel and sand deposits were it not for the marine fossils found in them. Holden, following Hyde, interprets the Black Hand conglomerates as delta deposits, laid down in marine waters, cross-bedded by the continuation of river currents into a shallow sea, and not greatly influenced by wave action or shore currents. The coarse materials could be deposited as deltas by streams of considerable volume, steep gradients, and short courses. The shale facies are thinner, alternate in a horizontal direction with the conglomerate facies, and are areas of silts, clays, and finer sands.

The gradual thinning of the conglomerate masses to the north, accompanied by evidence of weaker currents and marine conditions in deeper water, is indicated by finer sands, fewer and smaller pebbles, and the disappearance of the cross-bedding, so well developed farther south near Toboso and in the Hocking Valley area. The contrast is well shown, in comparing the Black Hand conglomerate facies in the Mansfield area with that in the Toboso-Hanover area.

One argument against the deltaic origin of the conglomerates is that delta sedimnets are rarely of coarse gravel. These sandstones and conglomerates were deposited under conditions of strong current action, which swept pebbles, up to an inch and more in length, to their present position. Thick beds were laid down over wide areas, at inclinations of 5°–15° which is believed to be steeper than the foreset beds of existing deltas. There is pronounced cross-bedding of both the irregular cut and fill and the regular inclined bedding, and on the eastern side of the Hocking Valley area there was deposited thick, coarse conglomerate beds in a northeasterly direction at angles of 15°.

The elongate, lobular shape of the Toboso, Hocking Valley, and River Styx facies suggests the projections from a delta. The cross sections suggest a broad channel, and the structures observed in the cross-bedded conglomerates are like those Barrell regarded as indicative of river-laid sands and not of deposits made by waves or currents.

According to Hyde (1915, p. 767) the materials in the conglomerate facies were accumulated under subaquatic and probably submarine conditions because they make a rapid lateral passage into marine beds; oscillation ripple marks are present on inclined bedding planes between sharply cross-bedded conglomeratic sandstones over large areas and through great vertical ranges; worm trails are common in undoubtedly marine Waverly sediments; thin beds of soft clay are interbedded with inclined sandstones and similarly inclined. No mud cracks are present, and there is no evidence of oxidation, such as highly colored beds resulting from subaerial deposition.

One of the most interesting statements made by Hyde (1915, p. 767) is that the structures observed in the Black Hand conglomerate facies are very like those that would be expected in bars or spits built out in deep water, such as Sandy Hook, but perhaps with more cross-bedding. Because of the geographic distribution of the conglomerate masses along the belt of outcrop, Hyde cannot accept the bar or spit hypothesis. He does not believe it possible for two bars, the Toboso and Hocking

Valley facies, to be built alongside of and parallel to each other, simultaneously. Hyde believes that the evidence favors simultaneous accumulation. If the sediments are of deltaic origin, the Black Hand outcrop belts in central Ohio appear to be part of the floor of a marine interior sea, which lay just off the front of a delta and was invaded by lobes from it. The shore line was located at no great distance to the southeastward. The sea must have been one of quiet water compared with the open ocean; otherwise the waves would have destroyed the sharp lines of the boundaries of the facies,

BAR, SPIT, AND BEACH HYPOTHESES

Eastern Ohio, when the Black Hand member was being deposited, was near sea level. Embayments with quiet deeper water bordered the shallow seas where the coarser sediments were laid down. The western portion of the Black Hand member, represented by the Hocking Valley, Toboso and River Styx conglomerate facies, may be a series of bars, spits, or beaches, which were deposited simultaneously or in succession from east to west. Strong currents from the south and southeast account for the structural features described by Hyde, Holden, and the present writer.

Figure 3 shows the distribution of the conglomerate facies, and the shaly facies surrounding the conglomerate facies. This condition does not favor the deltaic hypothesis. The cross sections may suggest channel deposits such as might be present in shallow water on a delta. To others they suggest bar, beach, and spit deposits. Hicks (1878) considered it the structure of a sea beach. The contour of the top of the Toboso and Hocking Valley conglomerate masses is that of an arch. With the exception of cross section CC (Fig. 4), the contour of the bottom of the mass is more suggestive of a bar or beach than a delta. The abrupt transition between the conglomerate and shaly facies could occur in a delta. But the same sharp change can be present in a bar, beach, or spit. The elevation of the base of the sections (Fig. 4) is calculated from the altitude of the top of the Berea sandstone formation. This formation varies in thickness, its surface contour is often irregular, and the Berea may be somewhat deformed. There is also the possibility of local deformation of the Black Hand member. However, the unusual shape of the elongate conglomerate masses is not that of anticlinal structure.

The bedding in beaches has a seaward dip, and ripple marks appear on their surfaces. Fluctuations in height of sea water resulting from tides, variation in the transporting power of waves and currents and in texture and quantity of sediments, the slope on which the sediment is moved, and variations in the coincidence of these factors all produce cross-bedding. Thompson (1937, p. 733) found that 48 per cent of the slopes of beach laminae are between 0 and 3°, 34 per cent between 4° and 7°, 11 per cent between 8° and 11°, 4 per cent between 12° and 15°, and only 3 per cent at 16° or over. In contrast to these figures, he found that the angles of foreset slopes in deltas and sandbars of tidal pools have an average maximum declivity of 28°. In the lower foreshores of beaches, 57 per cent of the laminae are 16° or steeper, as compared with 3 per cent of the laminae in the upper foreshores of beaches.

The average dip of the bedding planes for all measurements made by the present writer on outcrops of the Black Hand sandstone in the Toboso and Hocking Valley

facies is 3°–10°. In much of the area, the dip is only 3°–5°. Fifteen degrees is the maximum, and that occurs in one locality, on the east side of the Toboso lobe. In this discussion of dips, one must remember that the present dips of the bedding planes are not the original ones, for the strata have been tilted to the southeast about 25 feet per mile and somewhat more in places, a result of regional deformation. Scooplike embayments, evidence of scour, and well-developed cross-bedding are common in beach deposits, and these are present in the Black Hand member. Beach cusps have been reported in the Black Hand member in north-central Ohio.

Ancient beaches thin rapidly and interstratify with marine or continental sediments. Ancient beach deposits are characteristically less than 40 feet; the Medina sandstone is less than 25 feet thick. The great thickness of the Black Hand conglomerate suggests gradual subsidence during the time the sand and gravel accumulated.

The distribution and structural characteristics of the Black Hand member suggest the possibility of deposition as bars or beaches in shallow water offshore.

ORIGIN OF THE MATERIAL COMPOSING THE BLACK HAND MEMBER

The origin of the materials which make up the Black Hand has been discussed and remains an unsolved problem. Herrick (1887) believed the material composing the Black Hand conglomerate came from the northeast. Hyde (1915, p. 769–771) believed that the source of the material was from a land mass to the southeast. He points out that the Waverly formations occupy the same position as the Pocono sandstone formation of the Appalachians and are generally regarded as the equivalent. The Pocono in northern Virginia, western Maryland, and south-central Pennsylvania consists of four members of which the second one is gray or white conglomeratic sandstone, the Purslane sandstone member. It is a persistent member along the line of the Appalachian Mountains and according to Hyde is comparable with the coarse sandstones and conglomerates of the Cuyahoga along the Waverly outcrop belt in Ohio.

The great difficulty appears to be in the problem of the correlation of the Big Injun sand with a source to the southeast. One petroleum geologist, who has been working in West Virginia, expressed himself as follows:

> "We cannot begin to solve this problem until we can correlate the texture, thickness and distribution data over all the area covered by the Big Injun. In many places, the so-called Big Injun of the driller, is part of the Weir, Price, Farmers, Greenbrier or McGrady formations. Until these can be correlated and eliminated from the areal Big Injun picture, very little progress can be made".

So far, satisfactory correlation with the Black Hand (Big Injun) of Ohio has not been possible. And at present there is considerable doubt that the source of the materials was to the southeast, as proposed by Hyde.

Dr. Gordon Rittenhouse of the United States Geological Survey, who has been working on the problem of the Big Injun, has not arrived at any definite conclusions as to the source of the material composing the Black Hand. Apparently, part of the Black Hand correlative of Pennsylvania was derived from the northeast or east, but this sand is different in composition and source from the sand in the extreme western part of Pennsylvania, all of Ohio, and most of Pennsylvania. The source of this

material has not been determined. The nearest locality from which the milky white vein quartz in the Black Hand conglomerate could have come was to the north and northeast, probably the Canadian Shield. If it appears that the source did not lie to the west, south, or east, the only alternative is to the north. The Sharon conglomerate of the Pottsville undoubtedly came from the north, and the pebbles in that formation resemble those in the Black Hand member.

All the observations made by Hyde, Holden, and the present writer appear to support the conclusions that the major beds dip northward. This is difficult to explain, unless one assumes that the currents came from the south and southeast. An alternate hypothesis would be that the dip of the major bedding represents the dip of northward-facing beaches. The fact that the evidence strongly favors the theory that the material was transported by currents from the south and southeast does not invalidate the hypothesis that the original source of the quartz conglomerate was to the north. The material may have been carried by waves and currents originally from the northeast and north, in the eastern part of the area of distribution, in eastern Ohio, and adjacent States, and later reworked and shifted westward to produce bars, spits, beaches, and deltas. The white quartz pebbles were probably reworked a number of times for they are well rounded by abrasion and indicate transportation from some distant source.

In northern Ohio, the Black Hand member, including a large part of the Waverly series, was removed by erosion at the close of the Mississippian period. A great disconformity marks the close of the Mississippian in Ohio. In some places in northern Ohio the base of the Pennsylvanian Coal Measures rests on the Cuyahoga formation, and in other localities the Sharon conglomerate lies not far above the Berea sandstone. There is not enough evidence to indicate how far north the Waverly series extended originally.

SUMMARY

The Black Hand member varies so much in composition within short distances that it is difficult to trace. When traced horizontally from the conglomerate masses, the beds thin abruptly, contain more shale, and the sandstones are finer-grained and do not exhibit strong cross-bedding and evidence of scouring action. The conditions under which the Black Hand member accumulated were variable such as those that prevail along a shore line where finer muds and sands were deposited in lagoons or quiet deeper waters offshore, or in beaches, bars, or deltas where stronger currents prevailed.

The facies are so distributed as to indicate that thick elongate masses of sandstone and conglomerate extend in a slightly west of north direction. They are marine, and the dip of the true bedding planes (3°–15°) suggests deposition in shallow water by rather strong currents with scouring action. All the evidence indicates that the currents came from the south.

It is probable that the Black Hand member was laid down in a shallow interior sea, in which beaches, bars, and deltas were developed. The presence of quartz pebbles from half an inch to as much as 2 inches in length in the conglomeratic facies, although not fatal to the delta theory, is not in harmony with observations which appear to indicate that finer sediments usually prevail in deltas.

The quartz pebbles are well rounded suggesting that they have been reworked several times. They were probably carried by waves and currents from their original site which was to the north or northeast and later reworked and shifted westward to produce bars, spits, beaches, and deltas. What appears to be a bar or offshore beach was built on the west side of the area.

The variable thickness and irregular contour of the top of the Black Hand member suggest an unconformity with the Berne conglomerate member at the base of the Logan formation.

The Black Hand member originally covered a larger area; a large part of the Waverly series was removed by erosion at the close of the Mississippian period.

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College of Wooster, Wooster, Ohio.

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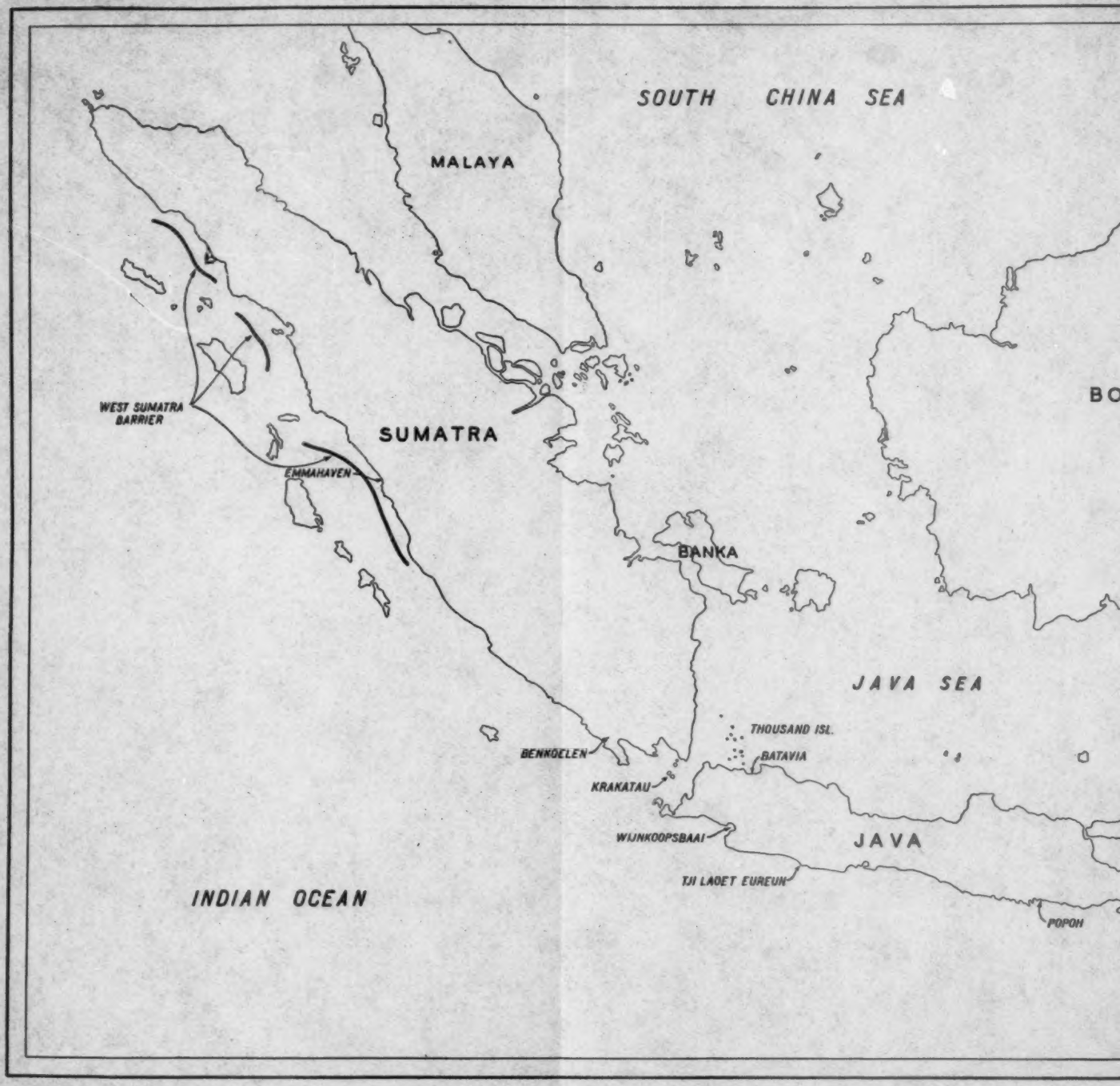
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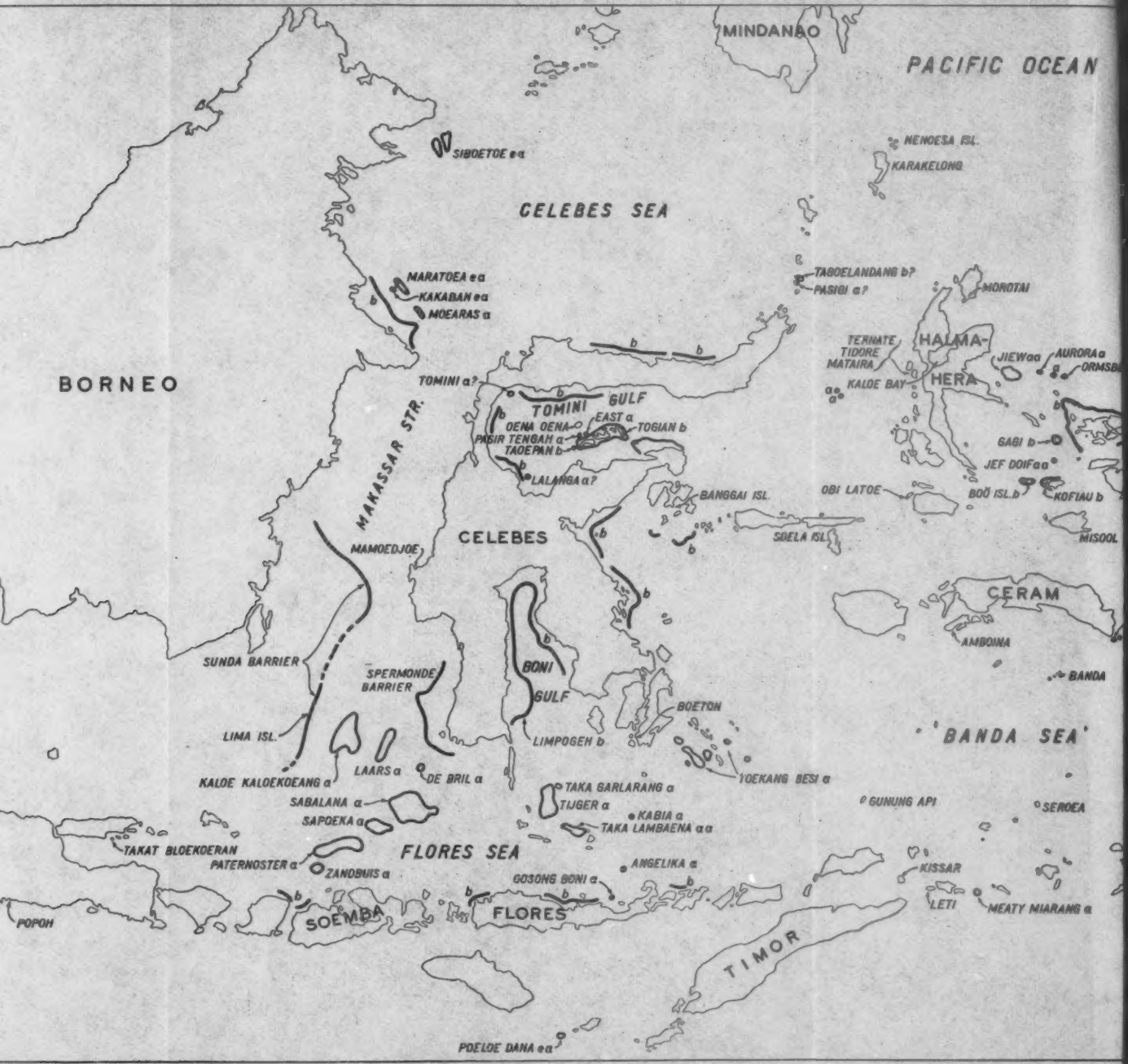


MAP OF THE EAST INDIES

Showing localities where investigations on coral reefs were carried out

a = AT
aa = AL
b = BA
ea = EL
eb = EL

re carried out

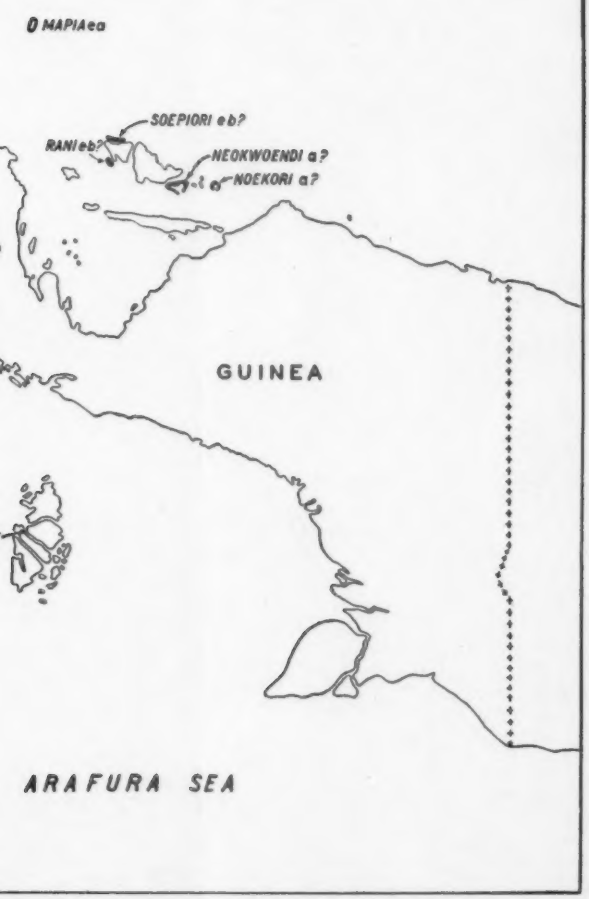
a = ATOLLS AND DROWNED ATOLLS

aa = ALMOST ATOLLS

b = BARRIER REEFS

ea = ELEVATED ATOLLS

eb = ELEVATED BARRIER REEFS



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CORAL REEFS OF THE EAST INDIES

BY J. H. F. UMBGROVE

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ABSTRACT

The writer reviews investigations on coral reefs in the East Indies carried out especially during the last 15 years before the war. Every atoll and barrier reef studied in some detail shows conclusive evidence of subsidence. The extreme thickness of some reefs, as demonstrated by their steep submarine slopes, cannot be explained by Glacial Control only. The influence of shifting sea level during the ice ages has been of minor importance on the East Indian reefs. In this region, as a rule, narrow lagoons are shallower than wide lagoons; the phenomenon is obviously related to aggradation of the bottom.

It is claimed that solvent action of sea water in the tropics is limited to action above the surface of the sea. The paper bears on the important influence of prevailing wind and wave action on the upper structure of reefs. Additional examples are given of sea currents as factors of morphological importance. The great influence of sedimentation and of a recent world-wide sinking of sea level is stressed. Elevated atolls, reef terraces, and tilting movements are considered. Results are mentioned of investigations on such subjects as the depth penetration of light and oxygen consumption.

INTRODUCTION AND ACKNOWLEDGMENTS

The paper is divided into sections based on the various subjects which are pertinent to coral-reef problems. The soundings mentioned in this publication have been

reduced to low-tide spring, *i.e.*, 7 decimeters below the mean level (according to the charts of the Dutch Navy).

On Plate 1 the localities are indicated in which investigations on coral reefs have been carried out. Dutch orthography has been used for geographical names; "oe" is to be read long "u".

The writer is much indebted to Professor J. Edward Hoffmeister of the University of Rochester who kindly read proofs for me and took care of any questions that arose after the manuscript was submitted to The Geological Society of America. Dr. T. Wayland Vaughan also kindly examined the manuscript and made valuable suggestions. To Mr. C. van Werkhoven of the Mining Institute at Delft I owe the excellent drawings of the bathymetrical charts.

INVESTIGATIONS ON REEFS AND CORALS

The charts of the hydrographical survey of the East Indies and Joubin's *Carte des bancs et récifs de coraux* (1912) show the great profusion of reefs in the East Indies. However, no reef drawn on these charts is a coral reef. The SIBOGA expedition, for example, studied reefs of Haingsisi near Timor that were predominantly built up by one species of nodular *Lithothamnium*, whereas corals were conspicuously absent. Fossil nullipore reefs of the same kind were mentioned by Martin (1911) from the Upper Tertiary of Rembang (Java). The following pages treat of coral reefs according to the definition of the term given by Vaughan (1919). To avoid misunderstanding, Figure 1 of Plate 2 shows a coral reef.

Studying the charts, edited by the Royal Dutch Navy Department, Niermeyer (1912) first showed that atolls and barrier reefs exist in the East Indian archipelago. The publications of Escher (1920), Van Vuuren (1919), and Molengraaff (1922; 1929) too are based on their studies of charts and fair sheets. In the nineteenth century only three naturalists studied East Indian coral reefs *in loco*—Hickson, Sluiter, and Studer. Hickson (1889) described a few coral reefs to the north of Celebes' northern arm. In 1890 Sluiter published his observations on reefs in the Bay of Batavia, the Thousand Islands, Krakatoa, and Emmahaven (W. Sumatra). Studer (1889) visited the elevated atoll, Paoloe Dana.

During my stay in the East Indies from 1926 to 1929 as a government geologist, I had the opportunity to study a number of reefs in some detail, *viz.*, the Bay of Batavia (1928a), Thousand Islands (1929c), Spermonde Archipelago, S. Celebes (1930a), Krakatoa (1930b), south coast of Java (Umbgrove and Cosijn, 1931), Emmahaven, W. Sumatra (1931a), and the Togian Islands, N. Celebes (1939a).

A short time after my arrival a zoologist, Dr. J. Verwey, carried out investigations in the Bay of Batavia and the Thousand Islands. Apart from biological papers he published also some geomorphological notes (1931a). And finally Dr. Ph. H. Kuenen, who joined the SNELLIUS Expedition in 1929–1930, has enriched our knowledge of coral reefs, especially in the eastern part of the archipelago. His observations and ideas have been published in one memoir (1933a) and two shorter papers (1933b; 1938).

The coral faunas of three reefs have been studied in some detail so that we have an

idea of the species of reef-building corals of this area. The writer has described from the Bay of Batavia the most complete coral fauna known from any reef in the world (1939b). In that paper 96 species of Madreporaria are described. And from the same reefs Verwey will soon publish a description of 21 species of *Acropora* in a monographic study on that genus. This makes the respectable number of 117 species from that small reef group.

I collected and studied, moreover, a suite of 91 species from the barrier reefs and atolls of the Togian Islands (North Celebes). The results of my study were published in 1940.

In 1907 Bedot described the corals from Amboina in which *Acropora* and *Porites* are only sparsely represented. At present 88 species of Madreporaria are known from Amboina. I have published a complete list of revised species names (1939b). In that paper (and again in the paper on the Togian corals) the geographic distribution of the East Indian corals on three other well-known reefs is given—Cocos-Keeling, Murray Island, and Samoa.

Detailed ecological investigations were carried out especially in the Batavia reefs by Verwey and the present author.

Verwey (1929; 1931a) also made detailed physiological studies on the Batavia reefs. His results on oxygen consumption, influence of silt, depth of the penetration of light, and the depth limit of coral growth will be dealt with below. Boschma published a paper (1936) on the growth rate of reef corals from the Edam reef in the Bay of Batavia.

Two naval officers, Verstelle (1931; 1932) and Luymes (1931), discussed the growth rate of a reef as a whole, comparing two subsequent reef surveys of the Navy in the Togian group. Fair sheets of the hydrographic charts are, however, not accurate enough to form a good base for considerations on that interesting problem, and no exact data bearing on this point are available from East Indian reefs.

Apart from the coral faunas mentioned, a great number of reef corals have been described from the East Indies. Quelch (1886) wrote about corals collected by the CHALLENGER expedition especially from the Aroe and Kei islands, Banda, Amboina, and Ternate. In 1899 the Dutch SIBOGA expedition brought home great collections of reef corals. Part of them have been studied—Fungidae, Agariciidae, and Eupsammidae by Van der Horst (1921; 1922), *Fungia patella* by Boschma (1923a), and the deep-sea corals by Alcock (1902). Boschma described a large collection of Fungidae from the Danish Expedition to the Kei island, Banda, and Amboina. Thiel (1932) published on corals collected by King Leopold of Belgium. Boschma (1923a) and Boschma and Verwey (1930) studied in some detail reproduction in *Fungia fungites*, *Fungia actiniformis*, and *Echinopora lamellosa*.

ORIGIN OF A REEF

INITIAL STAGES

The coral reefs in the Java Sea and the Bay of Batavia are rooted in a muddy bottom. Sluiter (1890) relates how numerous hard objects, rock fragments, shells, and especially pieces of pumice stone (which sank to the bottom after part of the orifices had filled with water) lie scattered all over the floor of the sea and form a con-

venient foundation for the beginnings of a coral reef. Species of *Acropora*, *Montipora*, and *Porites* are among the first colonies attached to such hard objects. And so we actually find coral reefs in every conceivable stage of development. The chart shows a great number of submarine reefs. Some are still small patches deep below the surface of the sea or nearly reaching the surface. Other patches just reach the surface and support a small sand island. The older cays are covered with dense vegetation.

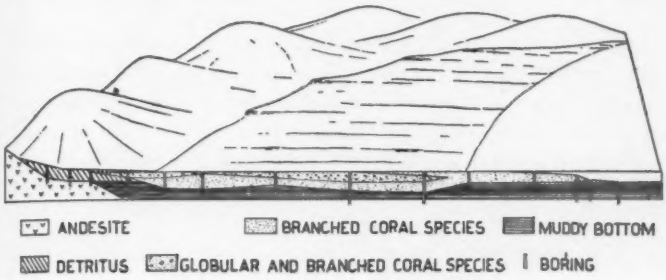

FIGURE 1.—*Schematic diagram of the fringing reef of Emmahaven, West Sumatra*

Conditions similar to those prevailing in the Bay of Batavia and the Java Sea are known from the Spermonde shelf (SW. Celebes), Emmahaven (W. Sumatra), and probably in many other areas. They may be seen fossilized in the Tertiary of Java. Right among the sands and clays of the Upper Miocene Tji Lanang beds we find pure coral limestone lenses in certain localities, as, *e.g.*, near Liotjitjankang and near Bandoeng, in the valley of the Taroem River, west of Tjimahi. A fine example, of early Pliocene age, may be seen in Gunung Linggapadang at Prupuk, Central Java.

Of special interest is the fringing reef of Emmahaven which was pierced by nine bore holes in linear arrangement (Fig. 1). From this valuable section we may gather the following particulars.

The reef has not grown on a rocky volcanic substratum or against the andesitic coastal lavas but rests on the muddy bottom of the bay, as do the reefs in the Bay of Batavia, the Thousand Islands, and the Spermonde Archipelago.

A layer of coral debris rests on the silty bottom, showing that in the initial stage, while the vigorous sedimentation of silt was going on, only a few branching coral species could grow. These branching corals gradually increased in numbers and formed the basis for the actual, more cohesive reef. In the later stages of development of the reef, these types again grow on the outside of the reef. Still later, bigger globular coral growths appear by the side of the branched varieties.

The same conclusion was made at Krakatoa. (*See* section on sedimentation under the heading "Coasts of Volcanic Cones".)

SINKING OF THE REEF AND AGGRADATION OF THE BOTTOM

The base of the Emmahaven reef lies about 4 meters deeper than the adjacent bottom of the bay, especially in the center where it has a thickness of 11 meters (Fig. 1). Sluiter (1890) tried to explain this by supposing that the reef, after it had grown into a compact mass, to a certain extent, gradually sank to the bottom of the bay.

The same phenomenon was noticed while drilling on small islands in the Bay of Batavia. Borings for fresh water on the sand cays of the islands Kuiper and Onrust disclosed that from a third to half the entire thickness (20–23 m) of the reefs lies below the level of the surrounding bottom of the bay.

This may have been caused largely by aggradation of the bottom as the rivers always bring a large quantity of silt into the bay. The reef has probably also sunk. From the available data it is not possible to ascertain the extent of their respective influences.

In any case aggradation of the bottom is an important factor. (*See* under the heading "Sedimentation".) From two surveys by the Navy in 1880 and 1912 it appears that the western part of the Bay of Batavia has shallowed about 1½ meters in 30 years, and the muddy coast line has grown seaward 200 to 600 meters (Verwey, 1931b, pt. III, p. 212, Fig. 4). An old chart of the Bay of Batavia, drawn by De Marre in 1722 (1753), shows near the coast line a few coral reefs that are now entirely buried.

OXYGEN CONSUMPTION AND THE INFLUENCE OF SILT SUSPENDED IN THE SEA WATER

Verwey (1931a, pt. II) carried out detailed physiological studies in the Bay of Batavia concerning (1) the oxygen production and consumption of reef corals and coral reefs, (2) the influence of sea currents, (3) the silt content of the water, (4) the depth of the effect of light, and (5) the depth of the living part of the reefs.

The oxygen consumption of a coral reef is enormous. Verwey found that *Acropora hebes* consumes more than 20 cc of oxygen per kilogram per hour. A reef in the Bay of Batavia consumes more than 4000 liters of oxygen during a night.

Movement of the water and especially sea currents bringing new supplies of oxygen are therefore of vital importance for coral reefs. Where they are absent reef growth may suffer greatly from lack of oxygen. For any reef in such a position the depth limit of the penetration of sunlight may be regarded as the only factor limiting depth of coral growth. The penetration of light was measured by the oxygen production of algae in jars hanging at various depths. Verwey pointed out that the light penetration is greatly influenced by the quantity of silt suspended in the sea water (silt measurements were carried out with the aid of Secchi's disc.). The data observed point to an obvious correlation between light penetration and reef depth.

The depth of the living reef was measured as follows. Under a diving hood Verwey walked down the slope of the reef and when he reached the lower limit of coral growth "at the margin of the layer of limy mud" he let a bamboo attached to a rope rise to the surface and then he measured the length of the rope.

A few data are combined in Table 1. For full data the reader is referred to Verwey's paper (1931a).

WIND AND WAVES

GENERAL STATEMENT

The influence of the wind shows very strikingly in the distribution of the debris of a coral reef that has been broken off and battered by the surf. We can distinguish

FIGURE 1. CORAL REEF OF SARAPPO, SPERMONDE ARCHIPELAGO, SOUTH CELEBES

FIGURE 2. NORTHERN PART OF THE ISLAND LEIDEN, BAY OF BATAVIA
Showing shingle rampart, moat, and north coast of cay.

CORAL REEF AND CORAL ISLAND

Island Leiden, Bay of Batavia. Photographed from a height of about 1000 meters. (*Compare* Figures 6 and 8.)

AERIAL VIEW OF A CAY

the fine detritus—for the sake of convenience called coral sand which is most easily carried away by wind and waves, and therefore is carried farthest—and the coarser fragments called coral shingle.

The finer erosion products are transported by waves bending around the reef and meeting at its leeward. Where sedimentation of the material takes place on that

TABLE 1.—*Measurements of depth of living reefs*

Islands arranged in order from the coast toward open sea	Depth of surrounding sea	Point at which Secchi's disc disappears from sight (mean values)	Light penetration (compensation point of oxygen production)	Depth of living reef
	meters	*meters*	*meters*	*meters*
Onrust	9–10	3.7	10–12	7–7½
Rotterdam	14–16	7		10
Hoorn	16–20	8.3	19–20.5	12
Haarlem	20–22	9.1		15

side of the reef a sand cay may originate, which eventually becomes covered with dense vegetation. In the very early stages, when only the bare sand flat just lies above the water, the wind, and in a minor degree the breakers, forces the sand into a crescent-shaped sand bar, the horns of which follow the direction of the alternate monsoons. In the older islands, this movement becomes more and more impeded by the vegetation, until in the end a rounded, slightly oval-shaped island is formed with proportionately short horns of loose barren sand, which change their direction with the prevailing wind.

On the other hand the coarser debris is heaped up on the windward side and may form shingle ramparts (Fig. 9; Pl. 2, fig. 2) that are highest on the side where the wind exercises its greatest force most regularly.

According to Verwey (1931b, pt. III, p. 202) the shingle rampart of the island Hoorn in the Bay of Batavia gradually slopes to a depth of about 5 meters where a submarine reef occurs over a distance of some tens of meters bounded by a steep outer slope down to about 12 meters below sea level. At that depth there are no living corals because of rapid aggradation of the muddy bottom. An analogous feature probably holds good for most of the reefs in the Bay of Batavia along their windward side. So we must understand that sand islands and ramparts are situated excentrically from the original compact reef. The more a sand island attains such an extreme position the less it is sheltered against the abrasive action of waves bending around the reef. So there may come a moment when abrasion will be stronger than sedimentation and the sand island will gradually decrease. Undoubtedly a recent negative shift of sea level is an important factor in the formation of both sand cay and shingle ramparts and the formation of a reef flat by abrasion (Fig. 9).

Another factor is of great influence on the development of shingle ramparts and the final destruction of the cay. In the Bay of Batavia a large quantity of huge coral colonies (principally *Porites*) are broken into pieces or even are blown up by native fishermen. Every year about 12,000 to 25,000 cubic meters of coral material is conveyed to Batavia for the hardening of roads and the building of houses (Harden-

berg, 1939, p. 238). Accordingly much of the reefs are destroyed, and the finer debris is heaped up by the breakers into new and fresh-looking shingle ramparts which are so characteristic in Batavia Bay. On the other hand, the strength of the reef is greatly weakened, and the abrasion of the cay is furthered by the constant artificial destruction of large *Porites* colonies. Comparison of the present Navy charts with an old chart by De Marre (1753) shows that 2 centuries ago the small sand cay of Schiedam in the Bay of Batavia was a rather large low-wooded island, and at that time the now-submerged reef "Vader Smit" was the largest cay in the bay!

As to the genesis of the moat, found under the lee of the shingle rampart, the author suggests the same explanation as already given by Mayor (1924b, p. 31, 35). The inward rush of water over the shingle rampart heaps up and must escape.

". . .all of it can not escape against the periodic rush of the breakers, so it constitutes a steady current flowing over the reef-flat parallel with the trend of the beach and escaping to the sea through any deep channel in the floor of the reef-flat. . .the remarkably uniform depth. . .represents a balance between opposing factors. . .If. . .the growth of coral ever became so luxurious as to reduce the depth of the reef-flat. . .the currents due to breakers and wind would become more rapid, and as everything alive or dead lies loosely upon the reef-flat, the floor would become washed down to a balanced state . . .If, on the other hand, disintegration of material and poverty of coral-growth caused the floor of the reef-flat to become deeper than 6 inches, the current would decline in velocity and fragments washed in from the lithothamnium ridge would not be removed from the floor, so that new material would soon restore the depth to its balanced state of about 6 inches."

Very commonly cemented sand banks lie between tide levels of cays. Kuenen (1933a, p. 56–58) frequently refers to these "beach sandstones," "beach conglomerates," and "cay sandstones."

From his observations on the reefs east of Australia, Spender concluded that the growth of mangrove swamps is favorably influenced by a protecting shingle rampart. The same situation was observed by Kuenen on the islands of Postiljon, Paternoster-Boö, and Obi Latoe. In other places, however, mangrove swamps occur without any protecting rampart. Undoubtedly Kuenen is right when he writes (1933a, p. 85):

"The principal reason for these latter cases must no doubt be sought in the comparative tranquility of the East Indian waters."

MONSOON WINDS

The reefs of the Indian Archipelago are within the monsoon zone. With regard to the influence of the monsoons, we distinguish the following possibilities, illustrations of which are plentiful in the Indian Archipelago.

(1) Both monsoons can blow without any obstruction or restraint, and their strength is felt to its fullest extent.

(2) The influence of one of the monsoons is screened off as the reefs occur on the lee of a large island with high mountains.

(3) The influence of both monsoons is weakened because the reefs are shut in on either side whence the monsoons blow.

In June 1939, when the East monsoon was blowing, Kuenen and the present author visited Takat Bloekoeran, a small sand cay in Madoera straits. We landed on a sandy patch of crescentic shape open to the west. However, under water a still larger crescentic-shaped sand mass could be seen, the two arms bent in the opposite direction (Fig. 2) showing that during the West monsoon the crescent is open to the east.

FIGURE 1. CORAL BOULDER
Large colony of *Diploastrea heliopora* (Lam.), on coast of Java's Southwest Point, Sunda Straits.

FIGURE 2. TOOTHED REEF EDGE NEAR TJI LAOET EUREUN, SOUTH COAST OF JAVA

FIGURE 1. MUSHROOM-SHAPED EROSION REMNANT IN A SHALLOW PART OF THE LAGOON WEST OF BATOE DAKA
Many balanids (*Tetraclita*) and oysters (*Ostrea mordax*) grow on the rock.

FIGURE 2. MUSHROOM-SHAPED ROCK ALONG NORTH COAST OF BATOE DAKA, TOGIAN ISLANDS

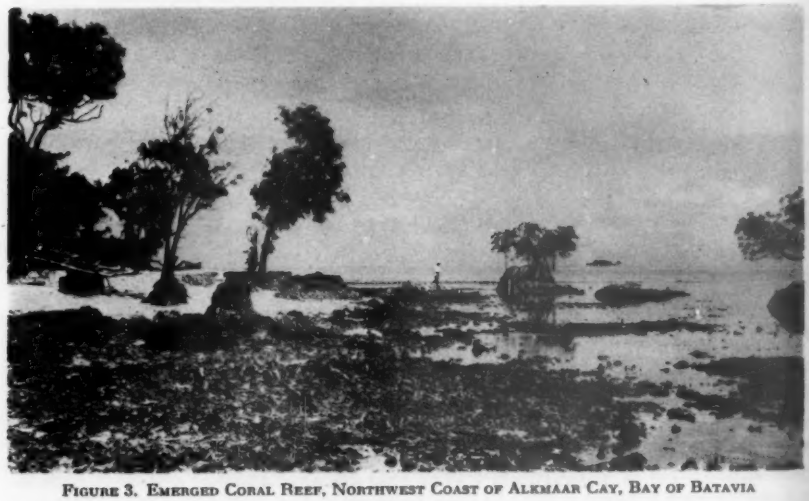

FIGURE 3. EMERGED CORAL REEF, NORTHWEST COAST OF ALKMAAR CAY, BAY OF BATAVIA

SOLVENT ACTION OF SEA WATER AND NEGATIVE SHIFT OF THE COAST LINE

Obviously the sand mass under water is acted on at a slower rate than the sand-flat that is directly opposed to the monsoon winds.

In the Thousand Islands (Java Sea) strong winds from the north-northwest prevail during the West monsoon, and from the east during the East monsoon. (*Compare* Plate 6 and Figure 13.)

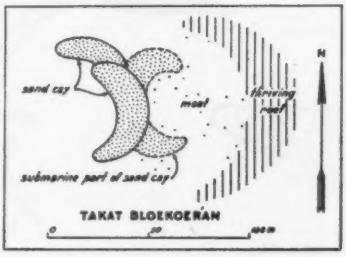

FIGURE 2.—*Takat Bloekoeran, a sand cay in Mandoera straits*

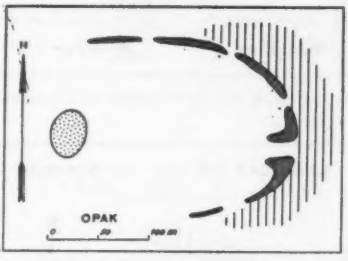

FIGURE 3.—*Gosong Opak, a cay in the group of the Thousand Islands, Java Sea*

Owing to very strong wind velocity from the east, the sand islands are situated on the west flank of the reef. The shingle rampart of the young islands (Fig. 3) emerges first on the east side; in the older islands these ramparts are highest on that side and consist of the largest debris. On the east side the cay is wave cut, and there is accumulation of sand on the west side (Fig. 4).

Thus the geological structure of the cays shows undoubtedly that the influence of the wind, and secondarily of the surf, is the strongest from east to southeast; the other wind directions show a much lesser influence. In other words, the East monsoon has more influence on the Thousand Islands than the West monsoon (being preponderantly north). These statements accord with the meteorological data; this point is fully treated and illustrated elsewhere by the writer (1929c).

I visited the Spermonde Archipelago (South Celebes) at the end of the East monsoon in 1928; its influence clearly manifested itself in the shape of the islands. Especially the small sand cays still uncovered by vegetation were crescent-shaped, the convex side turned to the east, resembling a sand dune or barchan (Fig. 5). The East monsoon obviously was not able to cause an analogous result on the shingle

ramparts I saw, but Kuenen noticed some slight accumulations of shingle on the east side of a few cays when he visited the group at the end of the West monsoon in 1930. Generally, however, the shingle ramparts show a quite opposite orientation. They

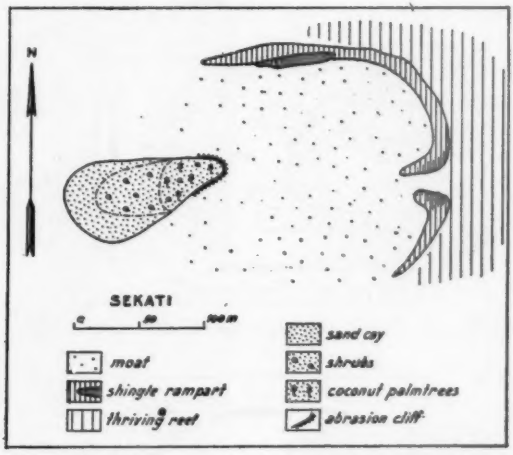

FIGURE 4.—*Sekati, a cay in the group of Thousand Islands*

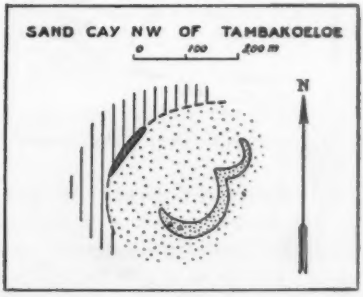

FIGURE 5.—*Tambakoeloe, a cay in the Spermonde Archipelago, South Celebes*
For explanation *see* Figure 4.

were found at the west side of the sandy islands, convex to the west; on the outer slopes the reef flourishes, on the inner side we find the shallow moat (Fig. 6); the sand islands always form the most eastern part, and as no high shingle rampart occurs on this side and no coral growth worth mentioning can flourish (because of the deposition of large quantities of coral sand there) the eastern sides of the islands always offer a good landing place.

Obviously the geological structure of the islands clearly depends on the preponderant influence of the West monsoon, which blows unhampered on these islands across the Java Sea and Makassar Straits. The force of the East monsoon on the contrary,

Bathym

INFLUENCE OF SEA CURRENTS

Bathymetrical chart of the Thousand Island group and the Bay of Batavia (*Compare* Figure 12.)

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when blowing across the Flores Sea, is broken, at least in the lower layers of the atmosphere, by the high mountains of South Celebes (which form a shelter for the Spermonde Archipelago against the force of the East Monsoon). The much lesser influence of the East monsoon is shown by the alternating shape of the sand cays; it is

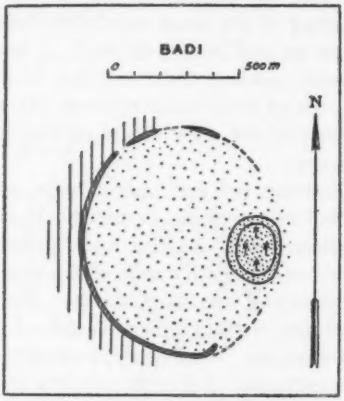

FIGURE 6.—*Badi, cay in the Spermonde Archipelago*
For explanation *see* Figure 4.

not strong enough to cause a permanent result in the orientation of the coral reefs, the shingle ramparts, or the sand islands.

In the Bay of Batavia the sheltered position of the coral reefs protects them from the wind. Precise data, collected on the spot, about the frequency and the velocity of the wind indicate that their morphology is most intimately connected with the prevailing monsoons. Data furnished by the Batavia Meteorological Observatory led to the following calculation: (1) the number of hours per annum during which the wind blows from each of the eight principal directions; (2) its mean velocity in these directions. The product of (1) and (2) ("wind effect") gives a series of numbers, which have been marked on the accompanying picture of the compass, next to the island Leiden. (*Compare* Figure 8 and Plate 3.)

This demonstrates very clearly that the influence of the monsoon winds and waves is just as might be expected from actual geological observations.

Along the western Togian Islands some reefs are protected from the influence of both monsoons. In a curve from west to north they are sheltered against the Northwest monsoon by the northern arm of Celebes; on the south of this group the eastern arm of Celebes breaks the influence of the Southeast monsoon, which, blowing across the Banda Sea, is only faint in the eastern part of the Gulf of Tomini. The reefs around the western Togian Islands are situated in a zone, famous for the unruffled calm and undisturbed quiet of the sea.

Neither on the barrier reefs, nor on the atolls, nor on the fringing reefs of the Togian Islands does one single shingle rampart occur. In vain I searched for *Montipora foliosa*, a coral that abounds on the outside slopes of the shingle ramparts in the areas

just mentioned, although it occurs in deeper water. On the Togian Islands it is impossible to distinguish facies types such as are discernible in the Bay of Batavia, the Thousand Islands, and the Spermonde Archipelago. Melobesiae are not entirely lacking, but they are confined to poor incrusting types. Nowhere did I find the noduliform lithothamnia that are not rare on the reefs in the Java Sea and near Makassar. Of the cementing of the corals into a lithothamnium ridge there is no question at all. There are no sand islands although, at low tide, the tops of many reefs are exposed. In short, nowhere could anything be observed connected with strong wind and waves, from which we must conclude that the wind does not affect the morphology and ecology of the reefs. Data on frequency and velocity of the wind in this area confirm this.

On the Togian reefs, however, not even sand islands occur, so that not a single trace of the action of wind or waves can be noted. How can this be explained? Spender, Crossland, Gardiner, Sewell, Kuenen, and I pointed out the important influence of the recent world-wide negative shift of the strand line that favored the formation of shingle ramparts and coral-sand islands. The three authors first mentioned are even convinced that, without a negative shift of the strand line, no structure above the water can originate. Conversely, a positive shift of the strand line is very unfavorable for the formation of shingle ramparts and coral-sand islands. It may be expected that they cannot originate in such an area. The Togian reefs lack all indication of a negative shift of the strand line, which indicates a recent subsidence of the bottom, as will be pointed out. Consequently, a positive shift of strand line probably accounts for the absence of shingle ramparts and sand islands. Furthermore there is not even the slightest indication of the influence of wind and surf on the Togian reefs.

LAND AND SEA WIND

In the Bay of Emmahaven near Padang (W. Sumatra) is a small coral reef. On the north side of this reef is a small sand island called Pasir Ketjil. It has lately been surrounded by brick walls, besides which a stone pier has been built in a southwest direction (Fig. 7). Since the building of that pier, coral sand has accumulated against it on the south side. This reef lacks shingle ramparts. From this situation of the sand island with regard to the reef, and from the placing of the younger coral sand accumulations (A in Fig. 7), it may be concluded that the maximum wind effect is from the direction of the open sea, about southwest. Monsoon winds do not occur in the coastal plain of Padang. The wind system in Padang is entirely dominated by land and sea wind, but the sea wind is always stronger than the land wind so that it may safely be assumed that the direction of the wind of 9 and 12 o'clock predominates (maximum wind effect).

Thus is appears to have been the effect of the sea wind—*i.e.*, the product of the wind frequency and the velocity of the wind—which we have recognized in the structure and situation of Pasir Ketjil. Full data may be found in my 1931 paper (Umbgrove and Cosijn, 1931). Although the frequency of the land wind is rather great its strength must be very little, for in the structure of Pasir Ketjil no influence assignable to the land wind is apparent.

DISTRIBUTION OF REEF ORGANISMS

Relative to the nature of the bottom (coral sand or shingle), the depth of the water, and the movement of the waves, several typical faunas have developed. These

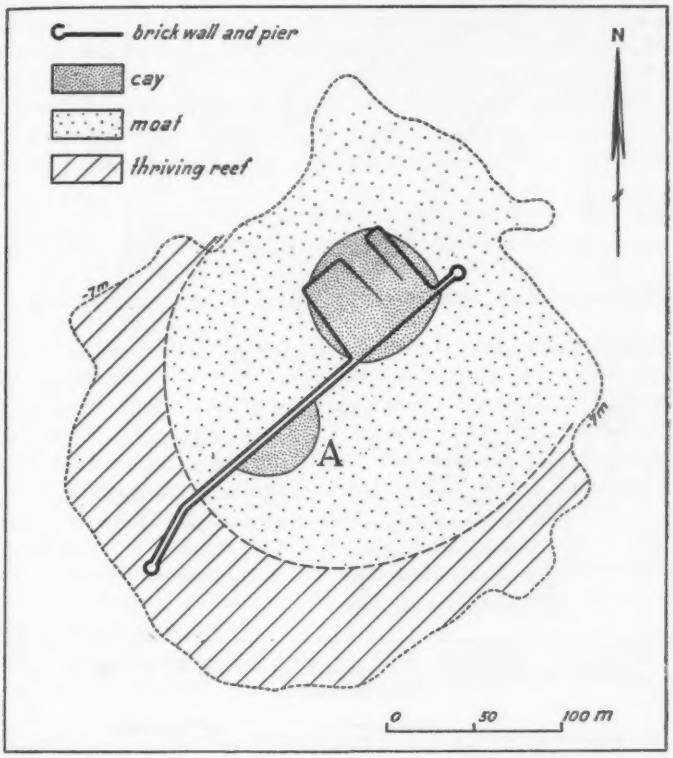

FIGURE 7.—*Pasir Keljil, a sand cay in Emma Harbor (Emmahaven), West Sumatra*

various combinations of special kind of bottom and conditions for life, each with a corresponding fauna adapted to it, constitute what in geology are called "facies."

We probably owe it to the smallness of the islands in the Bay of Batavia that the distribution of the different faunas is so apparent; some of them were mappable (Fig. 8; *see also* schematic block diagram, Fig. 9).

On the sandy bottom of the moat, in very shallow and warm water (up to 36°C), *Montipora ramosa* thrives, accompanied by a series of corals and other reef organisms that occur in this so-called "*ramosa* facies."

The shingle rampart represents the zone of the well-known lithothamnium ridge; but the genus *Lithothamnium* itself is rare in the Bay of Batavia. Other Rhodophyceae, however (*e.g.*, *Amphiroa*), thrive abundantly in this zone, which is called

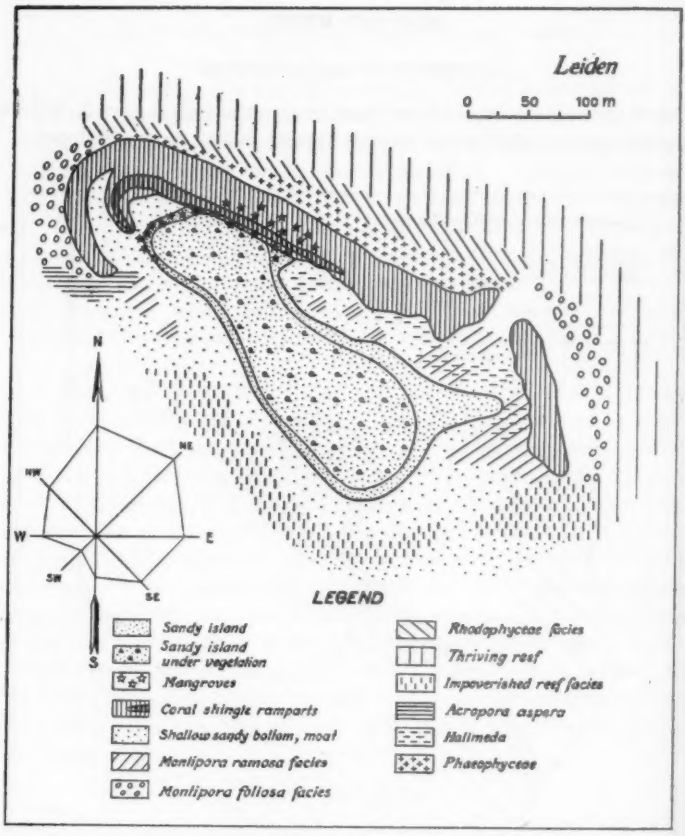

FIGURE 8.—*Distribution of organisms on Leiden cay, Bay of Batavia*
Compare Plate 3.

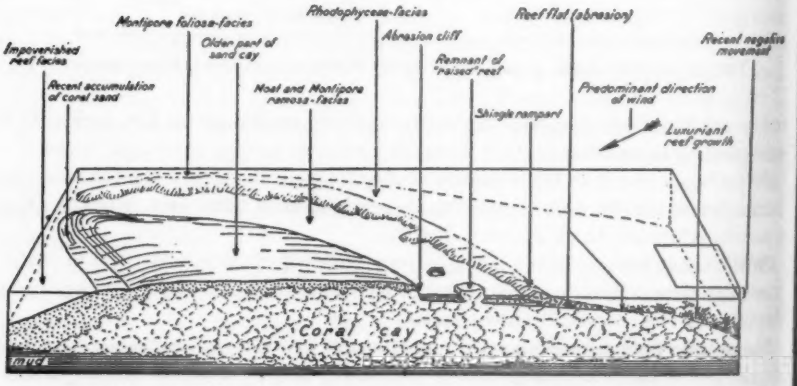

FIGURE 9.—*Schematic diagram of a reef and cay in the Bay of Batavia*

Rhodophyceae facies. Curiously, many types of branched growth are found in this zone. On the top of the wall, branched species of *Acropora* are above the water at every low tide.

On the outer slope of the shingle rampart, *Montipora foliosa* lives in great numbers; this fauna is found especially on the northwest and the southeast sides of the islands, the directions from which the wind raises the surf during the longest time of the year.

In deeper water, we find a great abundance of species, and very large colonies can be found there. This thriving reef, which is not completely mapped, is always developed around the island in an arch from west to north and east to south. In the sector from west over southwest to south coral-sand sediments occur in so large a quantity that few species of corals survive, thus forming the "impoverished-reef facies."

The ecology of the reefs has been treated at length (1939b). The reefs of the Spermonde Archipelago and Emmahaven show a similar distribution of facies types.

DESTRUCTIVE WAVES CAUSED BY CYCLONES AND VOLCANIC ERUPTIONS

The word "negrohead" or "niggerhead" has been applied by most authors to indicate coral boulders which are commonly found isolated on the surface of reefs and which have been washed up by big hurricane waves. The name has been used again by other scientists to indicate lumps of living coral in the deeper water of the reef.

Gardiner mentions the name "negrohead" when speaking about rock masses and pinnacles of limestone not loose but cemented to or being part of the reef beneath, sometimes even forming ridges or so-called "horses" (Gardiner, 1931, p. 34, 35). These formations originated as a result of recent negative movements. By disintegration loose blocks may have become broken loose and then rolled up into an immense boulder rampart, as described by Kuenen (1933a, p. 15, 73, 86) from the Postiljon and Paternoster islands.

Spender (1930) suggested abandoning the word "negrohead" and using the word "coral boulder" for the niggerheads which have been carried onto the reefs by storm waves.

These boulders are a common phenomenon on reefs in the area of the Great Barrier Reef and also on other reefs in regions of tropical cyclones.

I noted their absence on reefs in the Malay Archipelago where monsoons blow with great force, as on the Thousand Islands in the Java Sea, and the Spermonde Archipelago. This applies also to the Bay of Batavia, Emmahaven (W. Sumatra), and to the Togian Islands in the Gulf of Tomini (N. Celebes). From this one might conclude that, in regions where no cyclones occur, no coral boulders can be expected.

A latitude of 5° is the lowest in which cyclones do occur; between 6° and 8° latitude they are still very rare. The Malay Archipelago is situated only 6° north and a little more than 9° south of the equator. Consequently the conditions for the origin of cyclones are unfavorable.

Braak (1923) informs us that cyclones are occasionally met with in the extreme southeast of the Archipelago. Definitely determined cyclonelike disturbances are

known from the islands of Timor, Banda, Roti, Kisar, Leti, Damar, and the Kei Islands. According to him, "The islands north of Celebes are sometimes visited by the typhoons which pass to the south of Mindanao, as was the case with the Talaud islands in October 1904."

So one can see coral boulders on Timor and the neighboring islands. As far as I know we have no data on those places that either deny or confirm this supposition. Neither have I been able to find data concerning this in the Pilot Book for the East Indian Archipelago.

As to the islands between Celebes and the Philippines, some data can be found in the Pilot Book. From Salababoe, one of the Talaud islands, the following is mentioned. In the southern entrance of the sea arm between Salababoe and Karakelong are the islets Saha besar and Saha ketjil. These are covered with a dense vegetation and are surrounded by a white sandy beach, on which locally lie big rocky lumps of weathered coral.

The only localities where Kuenen saw negroheads during his cruise with the SNELLIUS Expedition were on the reef at the northwestern corner of Morotai, on the reef of the Nanoesa islands, and on the eastern coast of Karakelong (Talaud island group).

Outside this region, however, two examples of coral boulders along the coasts of the East Indian Archipelago are known to me. Here the cause has not been a cyclone, but disastrous waves caused by the volcanic eruptions of Krakatoa in 1883 and the Paloeweh volcano in 1928.

At the time of the great cataclysm of Krakatoa in 1883, "negroheads" were cast on the shores in great numbers by the big waves attendant on the eruption. Close to the lighthouse of Anjer some tremendous blocks of coral were thrown on the beach; the largest block lies about 100 meters from the shore and has a volume of 300 cubic meters.

In his standard work on Krakatoa Verbeek has located this block on his map. In 1927 I visited the same boulder, now thickly overgrown and covered with a luxuriant vegetation. Some smaller "negroheads" are scattered along the coast in the neighborhood of the lighthouse of Anjer. In 1926 I found big coral boulders, among which there were enormous colonies of *Diploastraea heliopora* (Pl. 4, fig. 1), on the coast of Java's southwest point where, in 1883, the lighthouse was destroyed by the devastating wave.

In his memoir on the volcano of Paloeweh, Neumann van Padang (1930) says that "the eruption of 4/5 August 1928 was accompanied by three sea waves reaching a height of 5 to 10 meters on the coast of the island itself and on the opposite part of the island of Flores." He reports that on the north coast of Flores a coral boulder of irregular round shape and about 10 cubic meters was thrown on the beach near Maoroleh.

These two examples are the only ones known to me from historic times. They illustrate, however, that coral boulders may occur on more reefs and coasts of the Archipelago and may have been thrown up by a disastrous wave caused by the eruption of a neighboring volcano.

POWERFUL SURF ON OCEAN COASTS

The cementing action of lithothamnia is of great importance on many reefs in the Pacific. However, no true lithothamnium ridge is found in the East Indies. In the Bay of Batavia and the Spermonde Archipelago the shingle ramparts represent the zone of the lithothamnium ridge. The genus *Lithothamnium* and other Melobesiae are, however, comparatively scarce in the Bay of Batavia, but they are present; some species are incrusting, others form nodular growths of irregular shape. However, they never occur in great profusion nor do they cement the shingle components so as to transform the shingle rampart into a solid structure. Other Rhodophyceae, however, thrive abundantly on the outer slope of the rampart—*e.g.*, *Amphiroa*.

Strong surf seems to favor the development of nullipores; but the land-locked seas of the East Indies offer no favorable conditions for the origin of the lithothamnium ridge.

On the Togian reefs in the Gulf of Tomini no noduliform lithothamnia occur. Melobesiae are confined to a few incrusting types. Of the cementing of corals into a "lithothamnium ridge" there is no question at all. The sea is in general but slightly agitated in the Gulf of Tomini, and the monsoons are neither hard nor constant; so their effect on the reefs is negligible.

On the other hand, lithothamnia flourish on those reefs of the East Indies that are open to the powerful surf on ocean coasts. On those reefs toothed reef edges of the type described and figured in detail in the Funafuti report have developed. The reef edge is characterized by narrow branched channels, partly covered and nearly perpendicular to the reef edge (Pl. 4, fig. 2). The landward side sometimes ends in a blowhole, and the surface of the "nullipore" ridge is terraced like rice fields showing rimmed pools. They have been described from the west coast of Sumatra by Erb (1905), Van Tuyn (1931), and by Umbgrove (1931a); from the south coast of Java by Cosijn and Umbgrove (1931); from the Nenoesa Islands and the east coast of Karakelong in the Talaud islands by Kuenen (1933a), and from the north coast of the Schouten islands by Feuilleteau de Bruyn (1921). These localities have been influenced by a slight negative shift of the strand line. Near the mouth of the Tji Laoet Eureun, a small river on the south coast of Java, the sea water thrown up by the ocean surf on the slightly emerged nullipore plateau finds its way through a gap in a coast ridge consisting of a fossil dune formation, and shows the peculiar features of a waterfall which continuously pours sea water into the river (Fig. 10).

I refer the reader to the discussion of the rimmed pools by Kuenen (1933a, p. 82–83).

SEA CURRENTS

The erosive action of sea currents as a morphologic factor modelling the shape of a whole group of reefs is clearly demonstrated in the Thousand Islands, Java Sea.

Where monsoon currents are piled up between narrow passages, obviously strong erosive action must take place along the bottom. Indeed we then see deep erosive channels wherever such narrow passages occur.

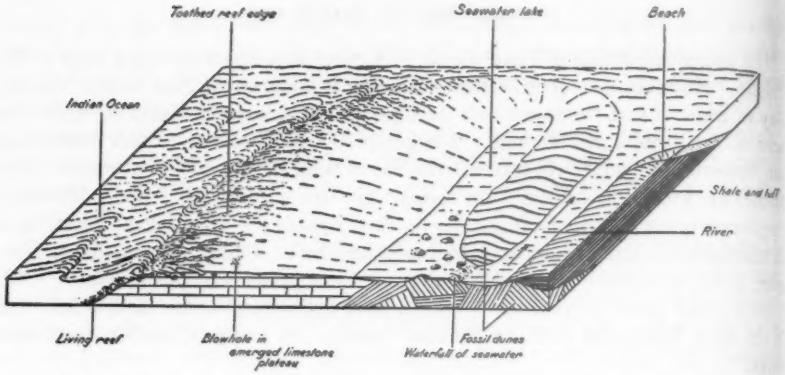

FIGURE 10.—*Schematic diagram of the toothed reef edge near Tji Laoet Eureun, south coast of Java*

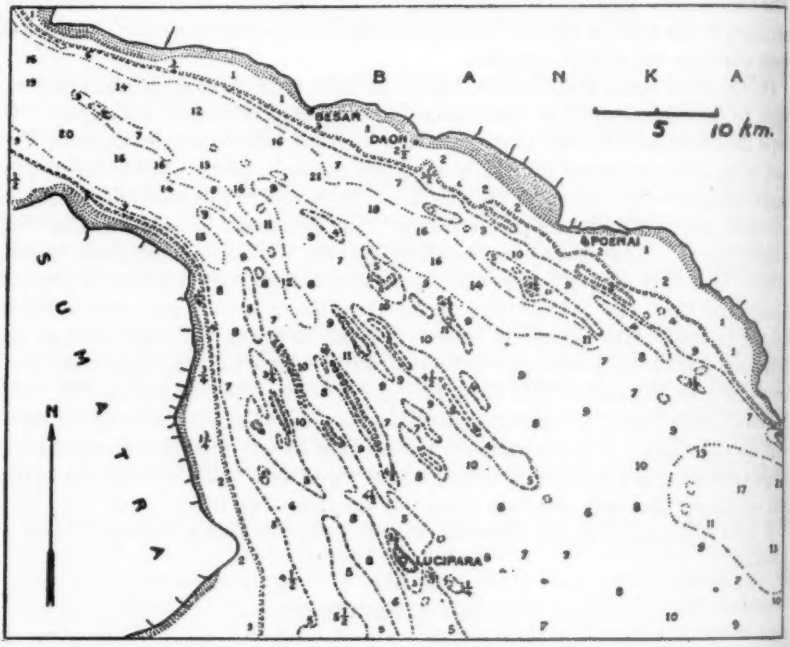

FIGURE 11.—*Arrangement of mud banks in Banka Straits*

When the masses of water once have passed these straits then the strong erosive action ceases; the rather abrupt blind ends of such erosive channels are characteristic.

Figure 11 gives a detailed map of the northern part of Banka Straits, drawn from the Navy Chart. We find here a number of narrow mudbanks, whose longer axes

are arranged according to the current, and we clearly notice how these elongate forms converge toward Banka Straits. This same phenomenon occurs in the channels between these mudbanks. Moreover, these are deeper as one approaches the narrows of the straits. The current through Banka Straits has eroded a channel, which is

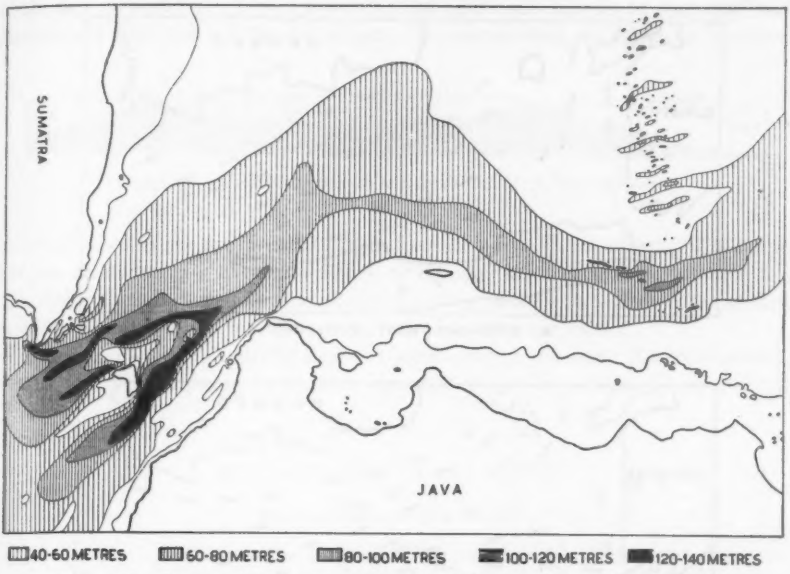

FIGURE 12.—*Bottom relief of southwestern part of the Java Sea and Sunda Straits Compare* Plate 5.

broad and deep in the Straits itself; as this strait widens outward, the erosive effect divides into a series of channels, which converge toward that strait and between which there are shallower banks.

We also observe this phenomenon in other straits—*e.g.*, Sunda Straits with the Thousand Islands. The reefs and islands of the group of the Thousand Islands all have a more or less drawn-out shape, and several islands are aligned behind one another in the direction of their longer axes. Figure 12 and Plate 6 elucidate this. The whole grouping of the island and channels gives the impression of having been eroded by a current directed toward Sunda Straits.

Comparing the oceanographic data on the currents in the Java Sea with the morphology of the submarine topography, the location of some of these currents coincides with deep channels, which we termed erosion channels on acount of their geomorphology.

Figure 13 shows two hydrographic charts, one for the West monsoon, the other for the East monsoon, which are taken from a paper by Berlage (1927).

A current runs from Banka Straits to Sunda Straits; in the bottom this is indicated by a channel. During the whole year a current flows along the north coast of Java,

8 months westward (6 months uninterrupted) and 4 months eastward (2 months uninterrupted), but the latter current may be twice as fast as the westward current. This current is indicated by the deep channels between the Thousand Islands and especially by the very deep channel between the Hoorn islands and the Agenieten

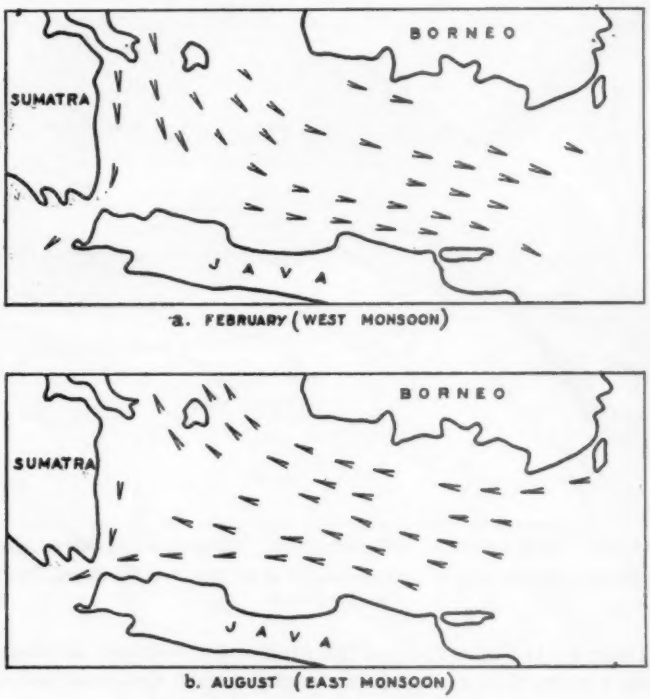

FIGURE 13.—*Sea currents in the Java Sea*
After Berlage.

where the current is probably strongest. In Sunda Straits this channel reaches its greatest depth, and there the rate of flow is stated to be 44 centimeters per second; in the open sea the rate of flow is 25 and 17 centimeters per second, respectively, for the West and East monsoons.

In front of Sunda Straits, as in the case of Banka Straits, a converging system of channels is formed, which shallow toward the open sea and between which only a system of banks remains, also converging toward the entrance of the straits. Their rather great distance from Sunda Straits (Fig. 12) forms the last unexplained part of the problem. When we regard the alignment of the whole group of the Thousand Islands (Fig. 12; Pl. 6) we recognize that probably there was originally a ridge-shaped elevation of the bottom. Here the recent system of sea currents met most resistance, and here the topography has been eroded as we see it today. In the lower parts on

both sides of this ridge there has also been erosive action, but only where the current is very strong and where it is cutting and deepening from Sunda Straits eastward can its course now be traced clearly in the submarine topography.

Figure 14 shows a schematic profile through the island Edam in the northern part of the Bay of Batavia. A bore hole near the lighthouse pierced 14 meters of reef material and then sank in a muddy bottom. The surrounding sea bottom is, however,

FIGURE 14.—*Schematic section through the Island Edam, Bay of Batavia*

23 meters deep to the south and 36 meters to the north of the island. The Edam reef now seems to cap a flat dome-shaped elevation of the bottom. Apparently this remarkable phenomenon is to be explained by the scouring effect of sea currents that have gullied out the bottom north and south of the present island.

The morphology of the parallel reefs in the Siboetoe group, north Borneo (Kuenen, 1933a, Fig. 38), probably is another example of the important influence of sea currents.

SOLVENT ACTION OF SEA WATER

MORPHOLOGY OF THE COAST

An important question for the coral-reef problem is whether limestone and dead corals can be dissolved by sea water. Murray and Gardiner strongly advocate solution, and they suggest that the formation of lagoons in atolls and barrier reefs may be explained in that way. In the same manner Sluiter considered the moat of Batavia and Thousand Island reefs to have originated by solution. On the other hand, chemical investigations by Vaughan, Dole, Lipman, Revelle, and others suggest that tropical surface waters in the sea are saturated and even supersaturated with carbonate of lime and therefore are unable to dissolve limestone.

From field observations I am convinced that ocean spray and waves may dissolve the surface of limestone exposed to the air. Cliffed limestone coasts and shallow submarine plateaus occur along the shores of many islands that are surrounded by coral reefs. Cliffed and corniced shore lines are often considered the result of mechanical wave action. This explanation is undoubtedly correct in most cases; the undermining wave action is accomplished by boulders and pebbles hurled against the cliffs. Along the Togian Islands, however, cliffed and corniced limestone coasts are protected from the abrading wave action by the surrounding barrier reefs. Moreover the lack of cliffs on neighboring coasts (surrounded too by a barrier reef) that do not consist of limestone proves that some process other than the mechanical action of the waves has formed the notches.

My own observations agree with the remarkable facts mentioned by Macfadyan (1930) in the Red Sea and by Kuenen in the East Indies. Kuenen saw that a "wave-

cut" notch "is also produced in positions where the force of the waves is entirely broken. In almost land-locked inlets the notch is practically as much developed as on the more exposed stretches of the coast, in fact, in the most exposed positions it is least well developed" (Kuenen, 1933a, p. 74).

As early as 1903 Martin described illustrations of the process from the Moluccas.

Although chemical investigation has shown that tropical surface waters are saturated or even supersaturated with carbonate of lime, I agree with Kuenen that geological evidence shows solvent action of the sea water, which seems limited between the tidal range.

> "Whether it is the greater range in temperature, the contact with the atmosphere, some influence of surface tension, the alternate wetting and drying or some other unsuspected influence which was overlooked in the experimental work, I am unable to say. I suggest that chemical research should be continued along experimental lines, also in nature, with a view to finding some such influence. Only by its discovery can the apparent incompatibility of chemical and geological evidence be eliminated" (1933a, p. 75).

In situ it became clear to me that organisms also disintegrate limestone on the level of the coves. It is principally the sea urchin *Echinometra mathaei* (Blainville) that occurs here in great numbers; it bores through the limestone and undermines it. Fallen limestone blocks are eventually, as it were, "bored up." In some places this process could be admirably studied. As a result of the "sawing" action of the sea and boring by the organisms into the limestone the steep undermined shore lines originate. Moreover, several very shallow submarine coastal terraces had clearly originated in many places near the shore, which are not abrasion terraces but have originated largely by the action mentioned above. The terrace itself is, practically everywhere, covered by fine "coral sand," but its presence is betrayed by its shallow character as well as by limestone remnants which here and there protrude in great numbers above the water. All these erosion remnants are more or less mushroom-shaped and are also undercut on the land side (Pl. 5). Eventually they become the victims of solution and of the boring organisms because their foundation has been "gnawed through."

Along the south coast of Batoe Daka from Tandjoeng Batoetingang to Tandjoeng Palada[1], the morphology of the coast changes abruptly. The steep corniced limestone coast makes way for sloping declivities without cliffs of the core of the group of islands, which consists of volcanic rocks and arenaceous sediments. There are no notches and no cliffs because the solvent action on these rocks is insignificant and because the echinoids do not bore into these insoluble rocks. The morphology of these shore lines is typical of a drowned landscape. Figure 15 shows an embayed valley on the north coast of Togian. These drowned valleys indicate a positive shift of the strand line.

The barrier reefs around Togian and Batoe Daka appear to be independent of the coastal type behind them, which in some places shows steep cliffs, in others drowned valleys. The situation of the barrier reef is determined by the steepness of the faults separating the group of Togian islands from the deep. (*Cf.* Figure 17.) The submarine relief is recent, probably Pleistocene or uppermost Neogene.

[1] These localities are east of the area of Figure 17.

EXCAVATION OF LAGOONS

As mentioned, the solvent action of sea water seems limited to the tidal range. No evidence was found that solution and other degrading factors might produce a lagoon be excavation. Vaughan had chemical studies made of the water in the Florida area

FIGURE 15.—*Embayed valleys along the north coast of Togian, North Celebes*

and concluded that lagoons cannot be formed by solution. Kuenen also has considered this question and put forward further evidence against degrading activities in the sense of Murray's and Gardiner's theory (Kuenen, 1933a, p. 110–114). On the contrary filling of lagoons is the normal feature in the East Indies as will be explained in the following section.

SEDIMENTATION

GENERAL STATEMENT

The occurrence of reefs grown on a muddy bottom has been mentioned. It is, moreover, a well-known fact that many coral species can remove some sediment from their surfaces. However, any coral buried in sediment will be killed by asphyxiation, as was demonstrated by Mayor (1924a).

It was also pointed out that the distribution of coral debris and finer coral sediment is caused by the prevailing winds. As a consequence of the wind- and wave-controlled deposition of coral-sediment conditions for coral growth are more favorable at the windward side of a reef than at its lee side. A coral reef grows more vigorously on the windward side because sedimentation is slight or absent.

Such is the modern version of the old theory of Eschscholtz—often erroneously named theory of Chamisso (*see* Sluiter, 1892)—who tried to explain the differences in coral growth by the hypothesis of different quantities of planktonic food. The following pages give ample evidence of the great influence of sedimentation.

COASTS OF VOLCANIC CONES

Davis (1928) was of the opinion that on the coasts of volcanic islands conditions must be adverse to the growth of corals, on account of the large quantities of erosion products that are continually transported into the sea. I saw a very convincing proof of this thesis at Krakatoa.

It is well known that, before the famous eruption of August 1883, the island Krakatoa consisted of three volcanoes—the basaltic volcano Rakata and the andesitic volcanoes Danan and Perboewatan. With the great explosion of August 28, Danan, Perboewatan, and the northwestern part of Rakata were entirely destroyed.

Subsequently a coral reef began to grow on the northwestern slope of the Rakata ruin at a spot called Black Point (Zwarte Hoek), a place where the basaltic lava of Krakatoa is exposed.

As we know exactly the year, even the day, when this new northern boundary of the island originated, this spot seemed to be the place *par excellence* to study step by step the development and growth rate of a reef after its origin.

Five years after the eruption Sluiter visited the spot and reported that living corals were growing in two places. At the west side of Black Point a fringe of corals, a meter broad growing on the basaltic boulders, had developed (west of A in Fig. 16); it consisted chiefly of a species of *Acropora* with branches 20–25 centimeters in length and some colonies of *Porites* and *Favia*. When, half a year later, he visited the same spot, most of this little fringing reef had been destroyed by basaltic boulders that had tumbled down from the cliff and smothered the reef.

In 1888 he found in the little bay west of Black Point only very small *Montipora* colonies, but on his second visit, in 1889, he found that nearly all the larger pieces of pumice that were lying in great abundance on the bottom of the bay served as a base for corals, which were of a branched type of growth and belonged to the genera *Acropora*, *Porites*, *Montipora*, and *Pavona*. (These spots are indicated by K on Figure 16.) Massive growth types were found only very exceptionally. Only very small colonies of *Favia affinis* were found; and no *Fungia* occurred. The fauna had suffered much from the pumice that had fallen down from the newly exposed wall of Rakata; accordingly this fauna of only branching corals shows a typical adaptation to these unfavorable conditions.

In May 1929, however, I found no living coral; we dredged only pumice. Everywhere the bottom seems to consist of that same loose and for the greatest part rather fine material. Although the sea was very calm the water was milk-colored by the

very fine pumice detritus in it. Certainly no coral is now living in the places indicated by Sluiter on his map of 1890.

Black Point is on the western boundary of the original Krakatoa island, and all the island west of Black Point consists of layers of pumice which fell during the eruption

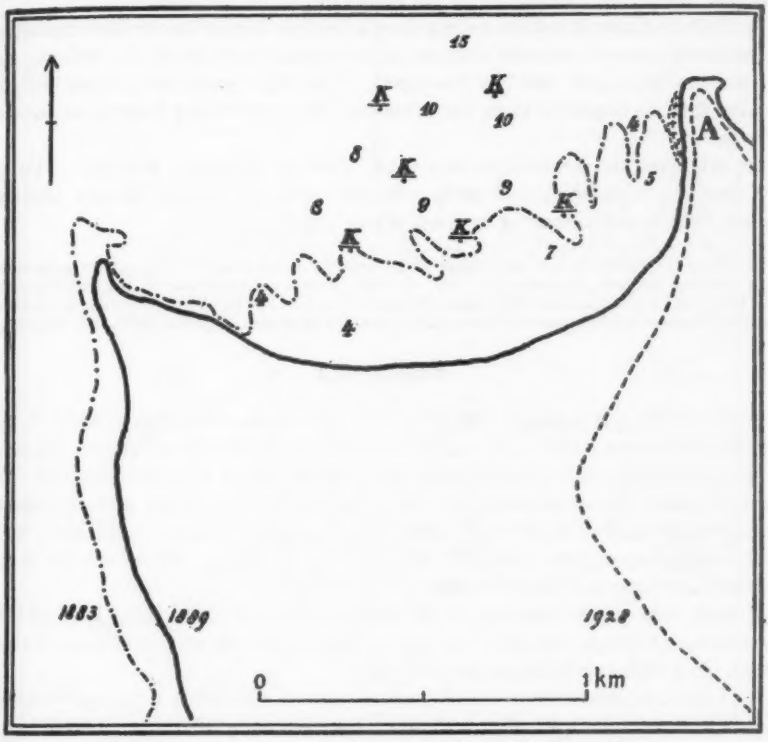

FIGURE 16.—*Successive coast lines near Black Point (A) Krakatoa*
K indicate places where coral growth was found by Sluiter in 1889.

of 1883. These pumice layers are attacked by the sea. Hence steep pumice cliffs with hanging valleys are formed.

Because of the very loose material of these pumice layers marine abrasion has already attained great extent, and, as the cliffs become higher and higher while the shore line is steadily moved landward by the action of the waves, they afford an increasing quantity of sediment in the sea.

In Figure 16 is given the data of Sluiter's report, showing the coast line of 1889 (as indicated by the continuous line), and the coast line of October 1883 (after Verbeek, indicated by the dot-dash line), and in 1928, according to the survey of the government steamer VAN GOGH and the map of the volcanological survey (indicated by the broken line). Since then the shore line, especially west of Black Point, has

moved still farther east. Therefore, in the rather short time since the eruption of 1883 a steadily increasing quantity of pumice has fallen from the steep cliffs that surround the little bay, and every vestige of coral growth has been killed, broken, or smothered by the immense quantity of material that partly covers the bottom of the bay and was partly transported by the waves farther off the coast.

As to the volcanic island Oena-Oena (north Celebes) I came to a similar conclusion. Corals are growing in separate colonies on the submarine slopes of that volcano, but no true massive coral reef has developed. The large quantities of boulders and smaller detritus deposited along the submarine slopes prevent a more luxurious reef growth.

On other volcanic cones conditions seem, however, different. Kuenen (1933a, p. 65) observed "flourishing and fairly extensive reefs on Ternate, Tidore, Maitara, Banda, Seroea, and Goenoeng Api near Wetar" and he says:

"For Tidore it was shown how the closing of the mouths of the streams by sandbars protects the reefs from too frequent smothering by silt. On Obi Latoe I witnessed one of the frequent floods that bring silt on to a very flourishing reef without killing it. The possibility of coral growth under unfavorable conditions was proved for the Aroe Islands, Perbatoean [Sapoeka atoll], and Obi Latoe."

MICRO ATOLLS

Jones (1910) and Krempf (1927) stressed the influence of sedimentation in the formation of micro atolls. They believed sediment accumulates on the central more or less horizontal part of large corals, thus killing the polyps in the central part. On the other hand, the steep sides of a coral colony are not buried and grow up forming a ring-shaped coral or micro atoll! According to Agassiz, Semper, and Risbec, however, a ring-shaped coral should be explained by the killing and excavation of the center of a colony that grows up above low-tide level.

Kuenen paid special attention to the micro atolls in the East Indies, and he is of the opinion (1933a, p. 64) that "both explanations must be used separately or combined, if we wish to explain all micro-atolls."

As Kuenen's observations are of great interest I will quote a passage from his paper (1933a, p. 65, Pl. VI, Fig. 4; Pl. VIII, Fig. 2) dealing with this problem:

"Conditions unfavourable to coral growth above low tide level certainly favour the formation of the micro-atolls, for these are generally found on the reef-flats. After the centre has been killed, especially as a result of the combined action of sediment and the more severe exposure to the rays of the sun and to rain, excavation certainly takes place. The surface of the 'lagoon' is frequently striated by the exposure of polyps that grow horizontally, their upper neighbours having subsequently disappeared. This process may go far enough to remove the entire centre of the colony, leaving a crescent-shaped form. The outgrowing rim may again spread inwards, so that the entire remaining surface is covered with living polyps. The upper surface of the rim is sometimes killed in its turn and separates two living vertical cylinders, one facing the 'lagoon', the other the open sea. More complicated forms also exist in which a set of crescents of living polyps at various levels and facing in all directions are found. The killing of the central part is furthered by the growth of algae which also collect sand and dirt. This process may be studied step by step, commencing in colonies no larger than an orange, on the reef-flat of Wotap. On the same reef-flat the larger micro-atolls are all considerably higher on the seaward side, probably because the conditions are more favourable to growth in the direction of the surf.

"A curious case of the formation of micro-atolls in which the controlling influence of the water level is obvious, was found on the broad flat of Reinis on Karakelong in the Talaud islands. During ebb tide the sea leaves large, shallow pools on the reef-flat. In these, corals grow vigorously, but they are unable to raise their heads above the level of the pool, as then they would only be covered a few hours every day. The edges grow outwards to form large pancakes as thick as the depth of the

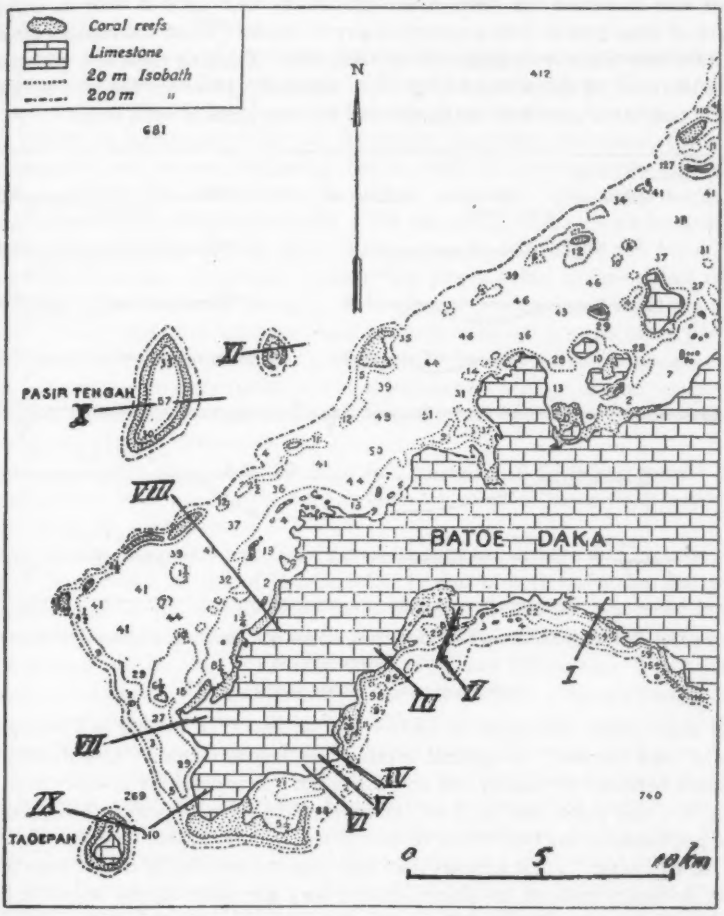

FIGURE 17.—*Western part of Batoe Daka one of the Togian Islands, Taoepan, and two atolls*
Location of sections I–XI of Figure 18 are indicated.

pool. I saw colonies of more than 1 meter in diameter. In these cases no excavation of the central parts had taken place."

DEPTHS OF LAGOONS

According to Gardiner (1931) a lagoon originates by solution and other degrading activities. Most authors are, however, convinced that the lagoon bottom is being aggraded. Indeed, filling seems the normal factor in the East Indies. The lagoons of the Togian Islands, North Celebes, offer convincing evidence (Fig. 17). In the Togian group reefs grow generally up to the surface of the sea and are exposed at low tide. The barrier reefs as well as the atolls fall away steeply into deep water. Often

I was able to admire the steep outer slope of the reefs covered with an enormous wealth of coral growth from a motor-dinghy or canoe. When the lagoons are deep, the inner side of the reefs appears to be steep also. Fringing reefs, too, are common along the coast of Batoe Daka (Fig. 17). Generally, however, the growth of coral merely consists of scattered tufts separated by open areas of coral mud.

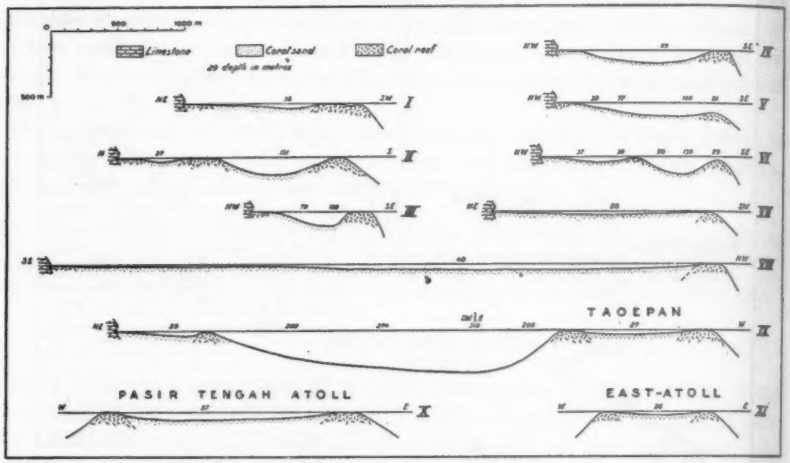

FIGURE 18.—*Eleven sections through the barrier and lagoons of Batoe Daka, Taoepan, and the two atolls the Togian Islands*

Location of sections indicated on Figure 17.

In some places the lagoon is narrow and shallow. In others, however, greater depths were sounded. In general depth of the lagoon seems to vary directly with distance between the barrier reef and the coast. It is desirable to enter more minutely into this point, first of all on the basis of the series of profiles I–XI (Fig. 18). The phenomenon has been noted several times by other authors in other reef areas. Davis, *e.g.*, says: " . . . it appears that large lagoons are usually deeper than smaller ones, evidently because, as already noted, they are more rapidly aggraded by inwashed material." (Davis, 1928, p. 2. *See also* p. 16, 135, 183, 192.) This is also evident from a comparison between our profiles VII and the northern part of II and VIII. In the same way the lagoons of Taoepan and East-Atoll, which are of about the same size, have similar depths (greatest depth 27, resp. 26 m), whereas the larger atoll, Pasir Tengah (Fig. 22), has a deeper lagoon (greatest depth 57 m). Some soundings on the south coast of Batoe Daka deviate from this rule. The southern part of section II shows a maximum depth of 131 m, section III 109 m, section VI 139 m. The explanation of these high figures becomes clear when we consider the location of the soundings on the chart or fair sheet (Dutch Navy Chart No. 192). From these it appears that the great "abnormal" depths in question occur where no closed sea-level barriers are present and where the lagoon sediments are easily lost to the deep surrounding seas through the gaps.

A consideration of the whole Togian area leads to the following conclusions (for full data *see* Umbgrove, 1939a):

(1) The above-mentioned connection between the depth of the lagoon and the distance from the barrier to the coast is proven if areas are compared that have a barrier that is entirely or almost closed and reaches as high as the level of the sea.

(2) Where the lagoons are wide and the barrier imperfectly developed, depths of 130–140 meters are common, indicating that the rocky substratum below the lagoon deposits is at least 140 meters below the surface of the sea. How much deeper we cannot calculate with the data available. Not too great a value should be attached to the figures indicating a greater depth, for the greatest depths (170 and 180 m) are near the rim of the lagoon and may indicate deep pits or gullies in the original relief.

(3) It cannot be said with certainty that reefs grow to a greater depth than 140 meters. A small reef knoll has been found not more than 400 m south of the deepest point (180 m), but it is impossible to prove that the reef has its foundation at such a depth. It might even have grown on a local unevenness (*e.g.*, an erosion remnant of the original landscape), so that the thickness of this reef cannot be determined with any certainty with the data available.

The depth figures south of Walea Bahi and Walea Kodi[2] do indeed suggest that the barrier must be at least 140 m thick; section VI, south of Batoe Daka, might be interpreted in the same way.

In my opinion, the points mentioned above force us to conclude that in the lagoon north of Batoe Daka, in that of Taoepan, and in that of both the atolls, the rocky substratum must lie at least 140 meters below the level of the sea. The great depths of 170 and 180 meters (west of the southern point of Walea Bahi) within the barrier do not prove a positive shift of the strand line of at least 180 meters. For it is not necessary to suppose that they originated by subaerial erosion of the landscape, originally situated above sea level. It is conceivable that they are the remains of deep gullies that had been scoured out about 40 meters below the then-prevailing sea level near their original mouths, by the combined action of river erosion and tidal streams.

(4) I entirely agree with Jones and Krempf that sedimentation plays a very important part in the morphology of the reefs. Either subsidence of the bottom, in the sense of Darwin's hypothesis, or Glacial Control may be an important factor in the origin of the barrier reefs and atolls. Without sedimentation disturbing the growth of the reefs, however—even if there were subsidence and abrasion—a shore reef would have originated and no barrier reef; in the same way a large patch reef and no atoll would have originated.

In the lagoons of the Togian reefs we see this principle illustrated by the fact that where the lagoon is deep (therefore where little sediment has been heaped up) reef growths occur in a number of places. In the deep lagoon south of Walea Bahi and Walea Kodi small reefs abound (so-called "knolls"). Such a phenomenon does not occur in shallower lagoons where a much more intensive heaping up of sediments took place.

Only where the reef could grow immediately against the rocky coast and is bounded

[2] Not on Figure 17.

on the outside by deep water does no lagoon occur. The southwest point of Batoe Daka and the south coast of Taoepan furnish beautiful examples (Fig. 17).

The steep outside slope is an exceptionally favorable place for reef growth because it is not hampered by sedimentation; the debris sinks at once to greater depth.

In connection with the relation of the lagoon sediments in the Togian Islands, we must point out some general aspects of what we might call the lagoon floor problem. I believe the depth of a lagoon floor represents a balance between aggradation and removal of sediment either by currents or by sliding down into the surrounding deep sea-trough gaps in the barrier reef or by some other set of regulating influences. (*Cf.* Davis, 1928, p. 217; Kuenen, 1933a, p. 112.) The problem of the depth of the lagoon floor may be compared to the problem of the rather stable conditions in the depth of the floors of a fringing-reef flat and the moat of a cay. According to my opinion Mayor has satisfactorily explained the latter, and I believe Davis, and Kuenen (1933a, p. 77), correctly point out that in glacial times the lagoons were washed out more or less to a level related to the level of the glacial ocean.

MOVEMENTS OF SEA LEVEL

GLACIAL CONTROL

The results obtained on the aggradation of lagoon floors mentioned in the preceding section do not favor Daly's Glacial Control theory. I will not enter into a full criticism of that theory here (*cf.* Ladd and Hoffmeister, 1936), but the facts known from the East Indian coral reefs are not compatible with Daly's theory (Umbgrove and Verwey, 1929; Umbgrove, 1930a; 1939a). At the end of a detailed discussion on the formations of East Indian barrier reefs and atolls Kuenen (1933a, p. 116) summarizes at least 20 arguments that contradict Daly's Glacial Control theory. In the following section it will be pointed out that the Glacial Control theory gives no satisfactory explanation for the barrier reefs of the Togian Islands. In their "Antecedent Platform theory" Ladd and Hoffmeister (1936) suggest

> "that any bench or bank—even one not 'smooth'—that is located at a proper depth within the circum-equatorial coral reef zone can be considered a potential reef foundation, and that, if ecological conditions permit, [*Cf.* section on Sedimentation] a reef could grow up to the surface without any progressive change in ocean level (p. 89–90). . .we do not believe that a rising sea level is essential to the formation of either barriers or atolls. Given a suitable foundation, either type of reef may be formed under stable conditions of depth by normal upward growth." (p. 88).

These statements do not mean, however, that Pleistocene changes of sea level are of no importance to coral-reef problems. On the contrary in any reef region that factor is to be considered, but it must not be overrated. During the Pleistocene the mean annual temperature was certainly lower, even in the tropics. The larger extent of moraines on some glacier-covered mountains of New Guinea may be considered proof of that. But coral growth was not notably influenced either by Pleistocene climate or mud control or by both in the East Indies, where there is about 70–100 per cent of still-living coral species in Pleistocene reefs, 50–70 per cent in Pliocene, 30–50 per cent in upper Miocene, and even 10–30 per cent in lower Miocene reefs. Lowering of sea level in the Pleistocene may have caused active attack of exposed reefs by the solvent action of rain and to some extent even by abrasion and may have caused a

degradation of the lagoon floor to a level related to the low level of the glacial ocean as mentioned in a previous section. (*Cf.* Kuenen, 1933a, p. 77, 78.) Rising sea level during interglacial and postglacial times may be considered favorable for the development of coral reefs in some places, and it may account for the upper 100 meters of

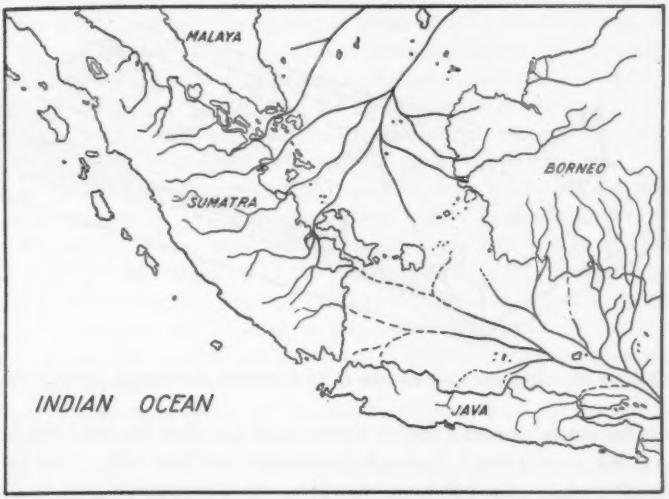

FIGURE 19.—*Map of the partly drowned rivers of Sunda Land*

atoll and barrier reefs, but it cannot explain the enormous thickness of the reefs that will be considered in the following section.

Are there any reefs in the East Indies which might be explained by upgrowth during postglacial times from a foundation now about 100 meters below sea level? We are not sure, but the following may show an interesting example.

Following Molengraaff's suggestion Borneo, Malaya, Sumatra, Java, and the shallow sea floor in between is now generally called Sunda Land. In Figure 19 the now-submerged system of rivers which Van Weel constructed on the strength of the isobaths in the South China Sea (the so-called North Sunda River) has been joined on one map together with the rivers drowned in the Java Sea, which I reconstructed in 1929 (the East Sunda rivers). It is well known that the Pleistocene Sunda rivers are thought to explain the great number of similar species in the fresh-water fish fauna of western Borneo and eastern Sumatra and other features of biogeographic interest.

Molengraaff (1929; Molengraaf and Weber, 1919) considers the series of reefs running parallel to Borneo's east coast along the edge of the shallow shelf to be a barrier reef—the great Sunda barrier reef with a total length of about 500 km—that grew up from a Pleistocene fringing reef of Sunda Land during the latest rising of sea level (Pl. 1).

One might, however, as well start from a real movement of the bottom instead of eustatic movements or one might think both phenomena combined and come to an

adequate explanation. The lands surrounding Sunda shelf show numerous signs of Pleistocene and post-Pleistocene movement. Thus I agree with Kuenen who says (1933a, p. 115): "Nothing opposes the theory that the Sunda shelf is possibly sinking slowly."

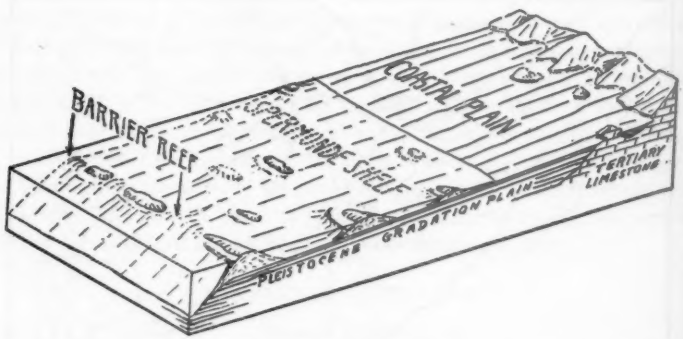

FIGURE 20.—*Schematic block diagram of the Spermonde Archipelago, South Celebes*

That is the reason one feels doubts about the theory that the great Sunda barrier reef has grown up as a result of postglacial rising of sea level only. And our doubts are strengthened by the following example. On the opposite side of Makassar Straits another barrier reef, the Spermonde barrier, borders the Spermonde shelf of South Celebes. The Spermonde barrier reef rises from a depth analogous to the Sunda barrier reef. However, the Spermonde shelf rises gently from the barrier toward the coast, and there it passes gradually into the coastal plain of Makassar, which obviously belongs to one and the same gradation plain (Fig. 20). The coastal plain of Makassar rises up to 30 meters above sea level, where a whole series of remarkable sea coves and notches in the Miocene limestones mark the former extension of the sea.

Data fixing the exact time of origin of the cornices in the Miocene limestone are not available. They may date from postglacial, Pleistocene, or even preglacial times. If the origin of the cornices dates from preglacial or Thyrrénian times (that is from a time when the earth was free or nearly free from land ice caps and the sea level was about 50 meters higher than at present) we have to account for a subsidence of the bottom of 20 meters. If, on the other hand, the sea coves are of Pleistocene age one may imagine a rise of the land simultaneous with or shortly after the rise of sea level.

Whichever explanation may be correct, it remains a remarkable fact that, notwithstanding a movement of the land, the barrier reef is growing up from "normal" depth!

In only a very few cases was direct observation of the contact of reef and substratum possible. Kuenen described a conformable reef contact from Haroekoe (1933a, p. 45), and he found unconformable contacts of reefs against steep coasts at Padang, Sibutu, Morotai, Kisar, and Wotap.

RECENT WORLDWIDE SINKING OF OCEAN LEVEL

A small subrecent elevation of the coast has been observed almost universally, and as coral coasts are excellent geological tide gauges it is no wonder that they have been described from nearly all regions where coral reefs occur. Even as early as 1832 Stutchbury tried to explain these features in seeking a common cause for them. Daly thinks that a Recent worldwide sinking of ocean level of about 5 meters has taken place. In the East Indies a large amount of evidence supports Daly's theory. After I had published a number of observations on Recent elevation of coral reefs, all data available in the literature on coasts of the East Indies were gathered by Van Tuyn (1931) who summarized them in a map of the western part of the archipelago. Kuenen, however, added a series of new observations in the eastern part. He found (1933a, p. 61–73) three successive slight negative movements—*viz.*, a level of 4–5 meters, a second level of 1½–2 meters, and a third level of ½–1 meter above the present level of the ocean. These recent elevations are best explained as the result of a series of stages in the withdrawal of the ocean. For full data the reader is referred to Kuenen's (1933a) paper. Figure 3 of Plate 5 shows three levels along the northwest coast of Alkmaar, Bay of Batavia, photographed in 1927. It will be of great interest to know whether the same levels are of general occurrence also outside the area of the East Indies.

Originally Daly sought to explain the sinking of ocean level by a recent moderate increase of the Antarctic ice cap. Since then he has, however, offered another explanation, and he writes (1934, p. 163): "Was the emergence due to a belated, plastic adjustment of the earth's body to the water piled on the sub-oceanic crust when the last great ice-caps melted?" In general the bottom of the sea as well as the continents will react every time the height of the column of water resting on the bottom of the sea changes.

Anyhow it seems that the movement of sea level is of very recent time and acted much faster than tectonic movements generally do. This may explain the raised shore lines in a region like the Moluccas, which is famous as a region of tectonic movements. Kuenen mentions, however, a few examples where tectonic movements may explain local divergences, and the absence of raised levels on coral coasts suggests that these must have sunk.

The recent negative movements are of considerable importance for the coral-reef problem as the development of sand islands and shingle ramparts seems closely dependent on the emergence of reef flats. This interesting point was fully discussed by Spender (1930) and by Kuenen (1933a, p. 70–73).

SUBSIDENCE OF THE BOTTOM

ATOLLS AND SUNKEN ATOLLS

The facts, known from East Indian atolls which have been investigated in some detail, demonstrate that they gradually grew up on a subsiding sea bottom.

Kuenen has contributed considerably to the problem of the origin of atolls by his careful examination of the deeper slopes outside these reef structures and of the

general morphology of the surrounding sea bottom. The echo soundings of the SNELLIUS expedition and the fair sheets of the hydrographic survey of the East Indies give convincing evidence. To mention an example (Fig. 21): Taka Garlarang atoll rises abruptly from a depth of over 2000 m, and it is built on the side of a deeply submerged ridge running from south Celebes to the south. The Tijger atoll rises from that same ridge "like a chimneypot standing on a roof, but it is much broader than the crown of the ridge and has evidently built outwards on its own screes" (Kuenen, 1938, p. 98).

The most interesting atolls are situated in the Toekang Besi group, southeast Celebes (Pl. 7). After Van Vuuren, Escher, Rutten, Molengraaff, and Hetzel had offered theories on their origin, Kuenen paid special attention to these reefs during his cruise with the SNELLIUS expedition. The atolls and islands of this group show a linear arrangement, related to the tectonic structure of the substratum. A row of atolls on the southwest side is followed by a row of elevated islands, which is followed by another series of atolls and a last row of islands with elevated reef terraces (Pl. 7.) Lintea consists of an atoll on the west side, bordered by an elevated island on the east side. In the middle of the northeast coast of Kaledoepa Tertiary strata occur; they have also been found on Wangi-Wangi and Tomea by Hetzel.

Echo soundings prove the great steepness of the submarine slopes of the atolls down to 500 and 600 meters, resting on an undulating submarine plateau of 900 meters depth. The atoll slopes are as a whole steeper than the island slopes. Slopes of 40°–50° are common around the atolls; this feature can only be explained by the upgrowth of coral reefs, as neither a talus of loose material nor a submarine volcanic slope ever show such extreme precipitousness. Kuenen (1933a, p. 95–100) has given special attention to this point. These features are, however, very simply explained by a gradual sinking of the bottom on which the atolls grew up. Kuenen's opinion is that toward the close of Tertiary time reefs grew around the highest points of the anticlines of a slightly undulating plateau, which gradually sank several hundreds of meters. By block-faulting movements roughly parallel to the original anticlines and syclines some reefs were intermittently raised above sea level, while in the sinking blocks a series of reefs grew up as atolls. One of these atolls was slightly tilted (Lintea). The western row of atolls are oblong-shaped, according to the original anticlinal ridge on which they started growing. The eastern atolls are, however, round and scattered arbitrarily on a submarine plateau, which is now submerged about 1000 to 2000 meters. Hence, in this region the bottom has subsided 1000 meters at least.

The steepness of the submarine slopes is one of the most characteristic features in East Indian atolls; sometimes the declivities even approach the vertical down to a depth of 200 meters. They must consist of solid coral-reef structures and they were formed by upgrowth on a subsiding bottom. Moreover most of the atolls have grown on deeply submerged submarine ridges from which they rise abruptly and steeply to the surface. There is only one group of atolls on the northwest coast of Borneo (Moearas, Maratoea, and Kakaban) showing a different configuration of the bottom. These atolls rise steeply from an almost flat shelf about 300 meters deep.

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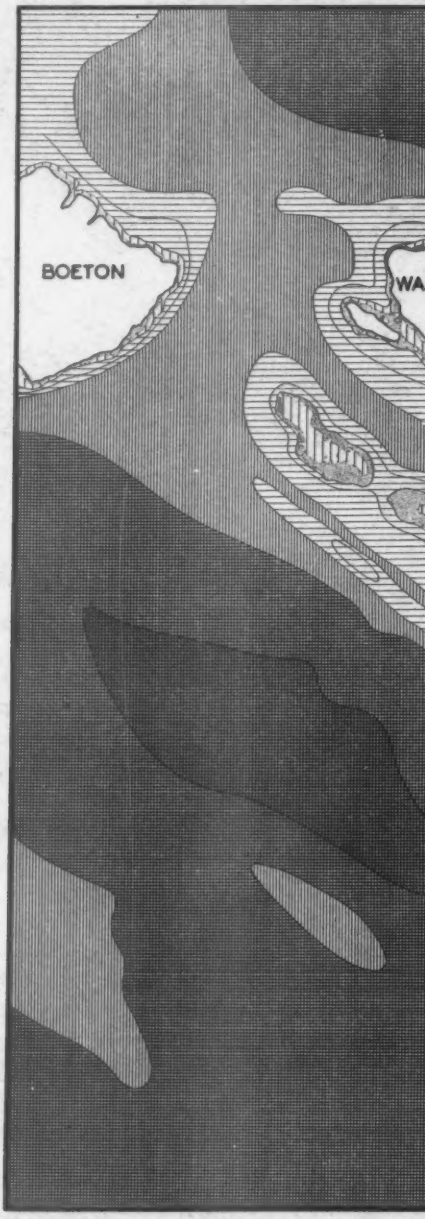

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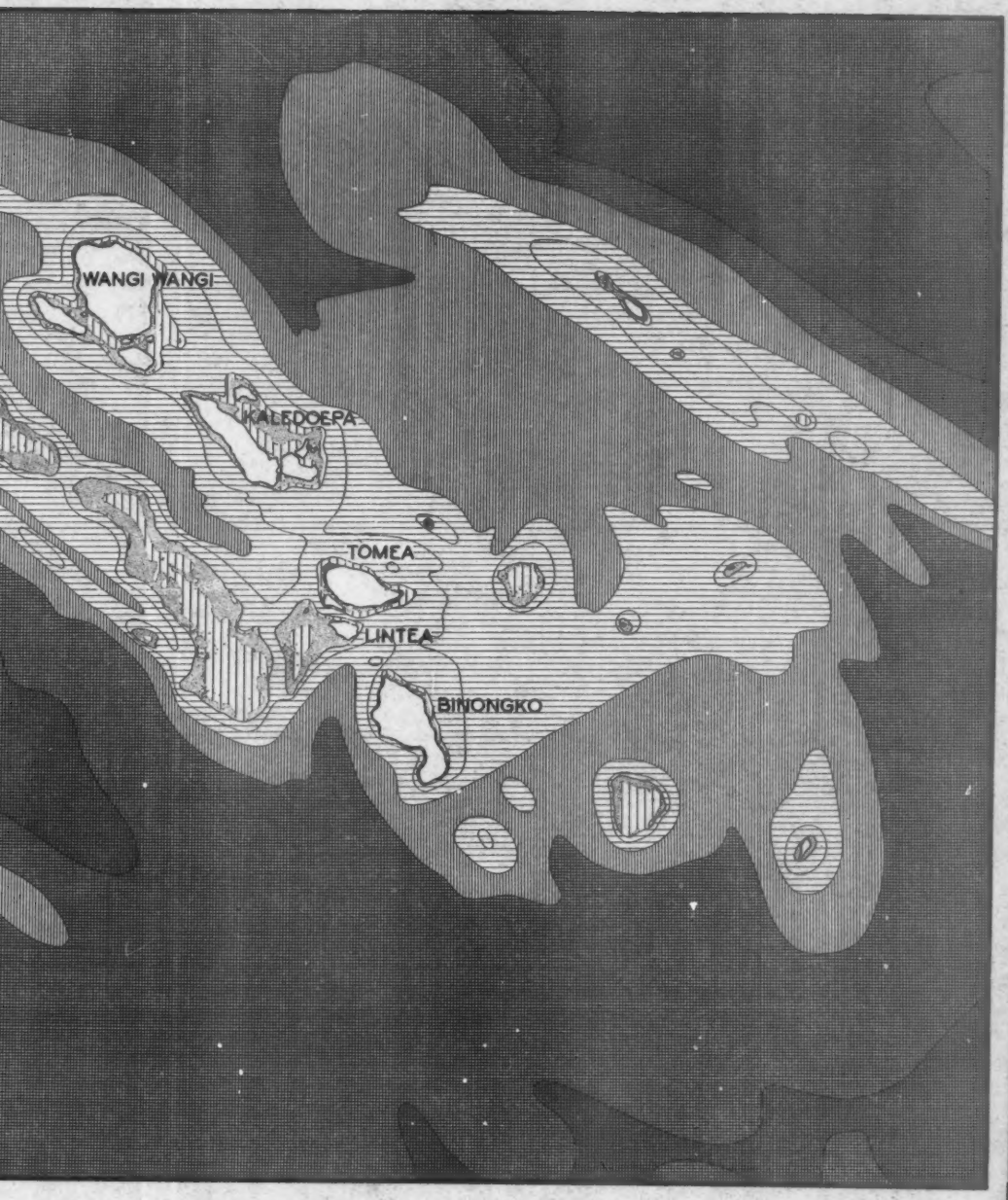

SUBSIDENCE OF THE BOTTOM

Bathymetrical chart of the Toekang Besi group, Southeast Celebes

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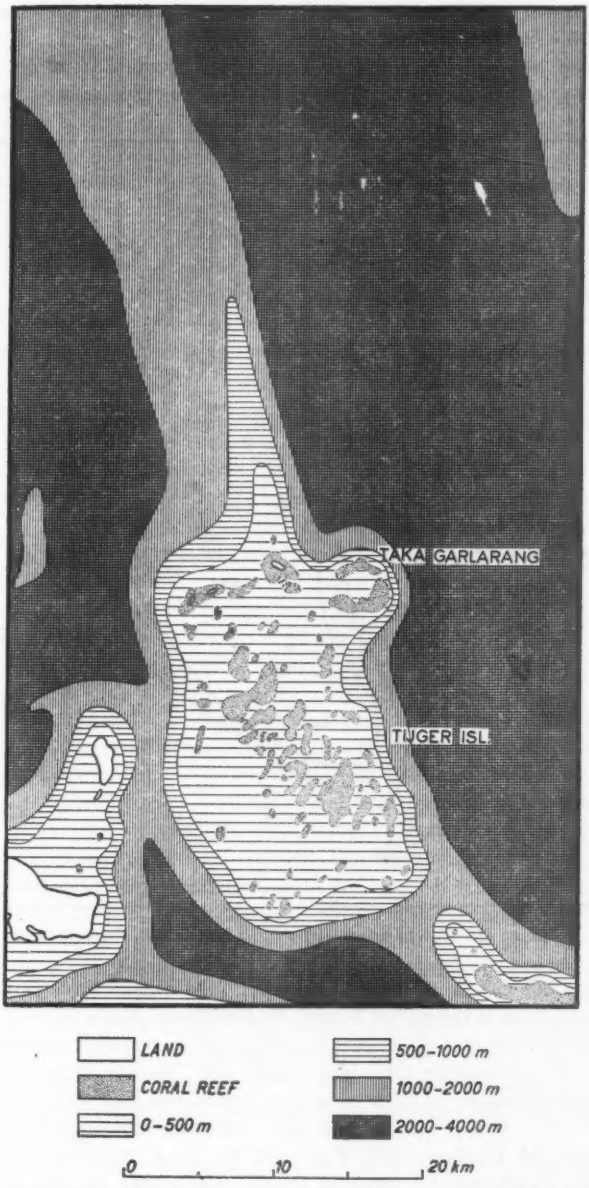

FIGURE 21.—*Bathymetrical chart of the region of Tijger atoll and Taka Garlarang atoll*

As Maratoea and Kakaban are elevated more than 100 meters they must have had their roots in a depth of 400 meters at least (Fig. 23).

Twenty-one atolls and atoll groups have been described from the East Indies. The following atolls were studied in place: Toekang Besi atolls, Sapoeka atoll,

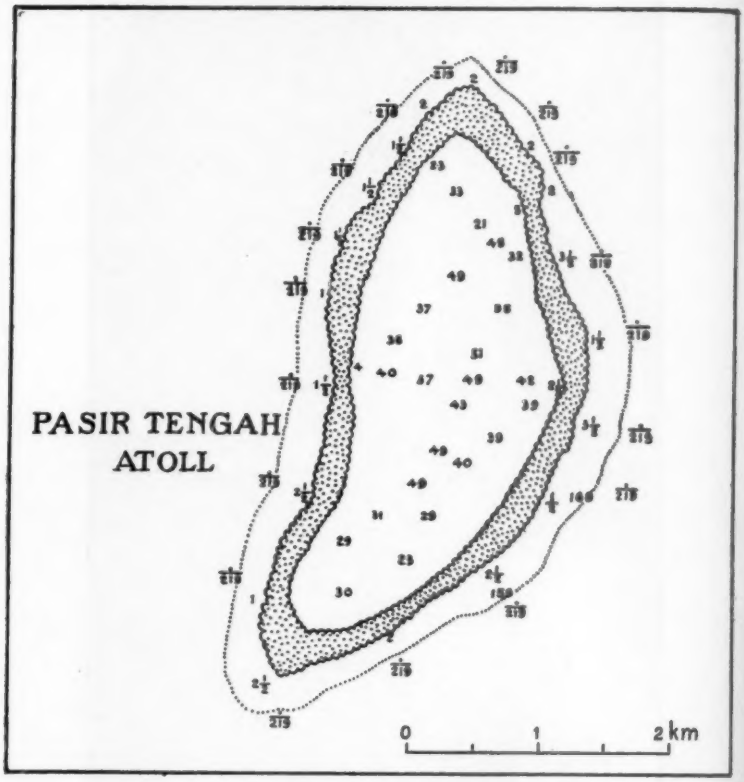

FIGURE 22.—*Bathymetrical chart of Pasir Tengah atoll, Togian Islands*

Paternoster atoll, and Sibutu atolls, by Kuenen (1933a), and Pasir Tengah (Fig. 22) and East atoll, both in the gulf of Tomini, by Umbgrove (1939a.)

Moreover the following atolls were described and figured by Feuilleteau de Bruyn (F), Davis (D), Niermeyer (N), Molengraaff (M), Kuenen (K), and Studer (S): East of Borneo, Moearas (N, M, K); southern part of Makassar straits and Flores sea, De Bril (N, M), Kaloe Kaloekoeang (M), Sabalana (M), Zandbuis (M), Maria Reigersbergen (M, K), Laars (M), Tijger (M, K), Taka Garlarang (K), the almost atoll of Taka Lambaena (D), Angelica (N, M), Kabia (M), Gosong Boni (N); surroundings of the Banda Sea, Meaty Miarang or Brisbane (N); west of Halmahein, two minute atolls (K); between Halmaheira and New Guinea, Aurora (K), a nameless

atoll east of Aurora (K), Ormsbee (K), and the almost atolls Jef Doif (K), Poeloe Jiew (K), and Ajoe (D, K).

The following statements seem very doubtful: Pasigi (North Celebes) described and figured by Hickson (M), Gisser (east of Ceram) described by Weber (M), Goram and Watu Bela described by Wallace (D), Neokwoendi and Noekori, north of New Guinea(F); a reef southwest of Tomini and the Lalanga reef in the gulf of Tomini. (N, *See* Wichmann, 1912.) As the Agenites, Boompjes Island, and a few other reefs in the Java Sea have a moat, they were erroneousy named atolls by Sluiter and Niermeyer. (*See* Wichmann, 1912.)

In the Ceram Sea the SIBOGA expedition dredged large quantities of recent dead reef corals covered with manganese from a depth ranging from 1304 down to 1633 meters and over a distance of 3 miles. Apparently this remarkable occurrence has to be considered as a drowned reef that has sunk so rapidly that the downward movement of the bottom could not be compensated by the upward growth of the reef.

BARRIER REEFS, SUNKEN BARRIER REEFS, AND ALMOST ATOLLS

In discussing Glacial Control we have treated already two barrier reefs. We pointed out that the region of the Spermonde barrier shows unmistakable signs of movement of the land. It remains doubtful whether the Sunda barrier reef grew up either as a result of the postglacial rise of sea level or on a subsiding bottom or by a combination of both factors.

I studied in some detail the barrier reefs of the Togian group in the Gulf of Tomini, North Celebes. I will mention here the results at greater length because they seem to give conclusive proof of a subsiding bottom and of the minor importance of Glacial Control.

In the central part of the group of Togian Islands sedimentary strata locally have been metamorphosed by volcanic eruptions (trachyte and andesite). Little remains of the original shape of the volcanoes. The Peak of Togian is a volcanic ruin in a fairly advanced state of erosion. Elevated reef limestones are widely distributed on the islands. They are grouped around the core of the archipelago like a flat terrace landscape. They are of an upper Neogene or Pleistocene age. The limestones must probably be regarded as a fossilized lagoon deposit. The reef within which this sediment was deposited has probably been eroded, either entirely or for the greater part.

Probably, in the geologically recent past, the group of the Togian islands was not yet surrounded by a deep sea. The steep northern and western boundaries indicated by the barrier reefs, which run at right angles to each other, very clearly indicate faulting (Fig. 17). We may reasonably suppose that coincident with the elevation of the block of the Togian Islands—which may be concluded from the raised reef limestone—adjacent blocks were submerged and produced the deep sea now surrounding the islands.

Recent movements along faults on the coasts of Celebes, accompanied by recent considerable elevations of the present Celebes itself, have been mentioned by other authors. This phenomenon forms the most striking characteristic of the eastern part of the East Indian Archipelago.

One is now confronted with the question: Did subsidence of the land occur or can the barrier reefs be explained by Glacial Control alone, or in another way?

We do not know to what depth the precipice on the outside of the barrier reefs is continued as the soundings are down only to 219 m deep and record "no bottom."

The aspect of the limestone cliffs does not warrant the conclusion that they originated through abrasion at a Pleistocene lower level of the sea. For it has been pointed out that coves and cliffs are still forming behind the shelter of the living barrier. Moreover the cliffed coasts occur by the side of sloping coasts with drowned valleys behind the barrier reefs. In a preceding paragraph we have concluded that the reefs rise from a depth of at least 140 meters. (*See* section on Depth of Lagoons.)

Even if abrasion occurred in the Togian group at a lower sea level during the Pleistocene, one would still be obliged to conclude that they subsided about 40 to 50 meters since then.

In my opinion, however, nothing in the submarine morphology indicates an abrasion phenomenon at a relatively lesser height of the sea level.

According to the Glacial Control theory one would expect that a submarine bank of 100 m depth should exist somewhere around the present barrier. This is, however, not found anywhere. (*Compare* Kuenen, 1933a, p. 99, 100.) Many soundings made along the outer slope of the barrier reached a depth of 219 m without touching a solid base.

A bottom at least 140 m below the level of the sea is deeper than the normal amount of the Glacial Control theory (90 m) Daly, 1934, p. 232). Consequently the reefs could not have originated as fringing reefs at a Pleistocene low level of the sea and grown upward into a barrier during the rise of the sea level; but during the Pleistocene lower sea level they must have grown as barrier reefs from a depth of 40–50 meters.

To maintain the Glacial Control theory, one would further have to suppose that the bottom remained stationary during the Pleistocene, or at least since the Riss glaciation. One must calculate from the Riss glacial epoch at least because it was the greatest glaciation and therefore caused the maximum lowering of sea level. For that maximum lowering of sea level is needed to explain a reef thickness of 140 m without subsidence of the bottom.

The situation now becomes even more complicated because raised reef limestone terraces occur. Accordingly we cannot suppose an elevation of the bottom during lower Pleistocene or upper Neogene time. Finally, it must, in my opinion, also be supposed that the bottom subsided in a very recent geological past.

With many others I am convinced of the truth of Daly's hypothesis that a recent worldwide lowering of sea level took place. Kuenen's researches and my own have shown many instances of this phenomenon in the East Indies. Although I was continually mindful of negative shifts of the strand line, and kept a sharp lookout for them, I discovered none on the Togian Islands. This negative characteristic suggests, in my opinion, a recent subsidence of the bottom.

Daly (1934, p. 232) writes: "Conceivably, too, there may be a few cases of subsidence of the reef foundations after the corresponding reefs began to grow up."

If we then abandon the stability of the bottom during the Pleistocene, we come, according to the Glacial Control theory, to the following reconstruction:

(1) Growth of the reefs that are now raised.

(2) Upheaval of the Togian area; erosion; subsidence of the neighboring areas (faults).

(3) Subsidence of the erosion landscape of the Togian fault block to 90–100 m below the present level of the sea, agreeing with the amount of the eustatic lowering of the level of the sea mentioned in (4).

(4) Lowering of the level of the sea to 90–100 m below the present sea level during the Riss ice age; formation of fringing reefs.

(5) Rise of the sea level during the Riss-Würm interglacial stage; growing up of the fringing reefs into barrier reefs; beginning of the subsidence continuing up to now.

(6) Lowering of the level of the sea during the Würm glacial epoch (to an amount less than 90–100 m); erosion of the barrier reefs.

(7) Rise of the sea level during the latest deglaciation, and simultaneously growing up of the barrier on the eroded reef structures of the former Riss-Würm barrier reef.

Even if we wanted to simplify this outline by making the foundation and growth of the reefs begin, not at the Riss glacial epoch, but at the last glaciation and deglaciation, one cannot evade the improbably representation that the land subsided to the exact amount needed by the Glacial Control theory for stable foundations elsewhere, then remained stationary for a period of time to enable the fringing reefs to form, and since then continued its subsiding movement. How much simpler this conception becomes when Darwin's hypothesis is applied in this area as shall be done below. It is therefore that I consider Daly's theory of Glacial Control to fail entirely as an explanation of the Togian barrier reefs.

My conclusion is that the contingent[3] influence of Pleistocene oscillations of the level of the sea must be considered of minor importance. On the other hand the facts admit of a simple explanation with the aid of the subsidence theory. Indeed, I do not doubt that this furnishes us with the right point of view with regard to the Togian reefs.

The following outline summarizes the chief points in the history of the reefs:

(1) Formation of the now-raised reefs during the (lower) Pleistocene, possibly upper Neogene.

(2) Upheaval of those reefs to an unknown amount (at least some hundreds of meters) above the level of the sea; erosion; subsidence of the neighboring fault blocks (faults, origin of the deep sea relief); beginning of the formation of the fringing reefs.

(3) Subsidence of the bottom of the Togian fault block, and growing up of the fringing reefs into barrier reefs.

The bathymetrical chart can indeed hardly be interpreted otherwise than that locally parts of the barrier could not grow upward fast enough to keep up with the positive change in the level of the sea; in other words, that they must be considered as drowned reefs. Section V of Figure 18 does not seem to admit of any other explanation. (For detailed charts *see* Umbgrove, 1939a.)

[3] It is even conceivable that the formation of the atolls and barrier reefs is so recent that it coincides entirely or in part with the latest Pleistocene movement of the sea level.

This phenomenon of drowned reefs might, in itself, have originated during the latest rise of the level of the sea and could not be taken as proof of the subsidence of the bottom. Since elsewhere the reefs reach the level of the sea across a large area, the growth of reefs, taken as a whole, has certainly kept pace with the positive shift of the sea level. Why this is locally not the case may find its explanation in factors for which we have insufficient data. (Sedimentation and biological factors may have played a part.)

As has been explained above, I have (for different reasons) reached the same main conclusion as Davis (1928, p. 370, 371)—namely that subsidence of the bottom played an important part in the origin of the barrier reefs of the Togian islands.

Kuenen (1933a) illustrates and describes in some detail the barrier and sunken barrier reefs of Kofiau, the Boö islands (p. 105), Gagi (p. 107), Waigeoe (p. 197–198), the intermittent barrier reef on the northeast coast of Borneo (p. 103; 1938, p. 98), the barrier reef (with faroes) south of the Banggai-archipelago (p. 111), and the almost atolls of Jef Doif, Poeloe Jiew, and Ajoe. In all these examples he could demonstrate their formation by subsidence.

In many localities the charts of the Dutch Navy demonstrate the existence of barrier reefs. In most cases, however, a discussion of their origin should be postponed until they have been investigated and their morphology known in detail.

Seventeen barrier reefs and four almost atolls have been mentioned by several authors, but only four barrier reefs were studied *in loco*—*viz.*, Spermonde, Togian, and Taoepan by Umbgrove, and Boö by Kuenen.

The following barrier reefs were mentioned and figured by Brouwer (B), Davis (D), Niermeyer (N), Molengraaff (M), and Kuenen (K): along the west coast of Sumatra (N, M), East Borneo, north of Cape Mangkalihat and to the south of the Great Sunda barrier reef (N, M), along the north coast of Celebes (N), along the northern, western, and southern coast of the Gulf of Tomini (N), along the east coast of Celebes (N), along the west coast of the Boni-gulf, S. Celebes, Limpogeh-barrier (N, M), to the north of Soembawa, Flores, and Adonara (N), Kofiau (K), Gagi (K), northwest of Waigeoe (K), south coast of Waigeoe (B), south of the Banggai archipelago (K), and Tagoelandang, North Celebes (M).

Moreover the following almost atolls aready mentiond were described and figured: Jef Doif, Poeloe Jiew, Ajoe (K), and Taka Lambaena southeast of Tijger-atoll in the Flores Sea (D).

REGIONAL SUBSIDENCE

Molengraaff (1916a) claimed that subsidence of volcanic islands in the Pacific would be brought about by slow isostatic downward movements, the subsidence continuing until the islands had reached the level of the simatic bottom, which he regarded, as Wegener did, as a viscous liquid. Molengraaff thus sought to explain the ultimate formation of thick coral reefs and the creation, in conformance with Darwin's theory, of a barrier reef and, finally, an atoll from a fringing reef by the gradual subsidence of the volcanic foundation. However, no strong downward movement is apparent in many of the Pacific islands, as has since been shown by observations along their coasts. Subrecent negative shifts of the shore line with a

height of approximately 6 meters occur in a number of these localities, and the world-wide distribution of this phenomenon proves that the sea level has lowered over the whole world in comparatively recent time. The discovery of an equal amount of negative shift on the simatic Pacific islands shows that the latter's subsidence (*i.e.*, assuming that they were really subsiding) has ceased. Vening-Meinesz' geophysical investigations show that the subsidence of volcanic islands in the Pacific is confined to the downbending of the ocean's simatic floor, and that the latter acts as an elastic sheet, and not as a viscous liquid, as Wegener and Molengraaff supposed.

Neither do the East Indian barrier reefs and atolls allow an explanation in the sense of Molengraaff's theory. The land-locked sea basins of the Malay Archipelago do not point to a simatic but to a sialic substratum (Umbgrove, 1934; 1938a; 1942). Moreover the larger barrier reefs encircle islands with sedimentary strata. And finally the barrier reefs and atoll groups discussed above cover regions of rather great extent. Thus the East Indian atolls and barrier reefs offer excellent illustrations of Darwin's subsidence theory.

ELEVATION OF THE BOTTOM

ELEVATED ATOLLS AND BARRIER REEFS

Kuenen visited the Maratoea and Kakaban atolls (Fig. 23) and published many interesting details, a map, and a few sections (1933a, p. 21–25, 103, 109). Maratoea has the shape of an elongated horseshoe and consists of a rim of raised reef limestone (½ to 2 km broad and up to 100 m high), which encircles a shallow platform studded with a few small low limestone islands. The raised rim shows several narrow winding channels representing passages through the former reef. One series of three soundings across the lagoon showed depths of 8.5, 5, and 7 meters. Kakaban has a narrow continuous rim about 150 m broad and up to about 40–50 m high; the lagoon is about 20–30 meters deep. At a distance of about 35 kilometers the normal (not elevated) Moearas atoll occurs. Maratoea and Moearas rise steeply from the outer edge of a flat shelf of 200–300 m depth, where it falls away abruptly to a great depth (Fig. 23).

Molengraaff (1922; 1929) has illustrated another elevated atoll—*viz.*, Poeloe Dana near Savoe. The elevated nearly closed limestone rim rises up to 36 meters and encircles a plain, probably the former lagoon bottom, which is now a few meters above sea level and bears two small salt-water lakes. Studer (1889) visited the island and mentioned large coral blocks resting on the tough clay of the former lagoon. Poeloe Dana is certainly worth a detailed re-examination.

In the case of Maratoea and Kakaban slow subsidence must have been followed by an upward movement of the bottom.

The reverse order of movements has taken place in the island Gagi (between Halmaheira and New Guinea). Gagi is 300 meters high and consists of a nucleus of peridotite surrounded by elevated reefs up to 50 or 100 meters. A barrier reef encircling part of the island is as a whole 50 meters below the surface enclosing a lagoon of more than 100 meters depth (Kuenen, 1933a, p. 107, Fig. 99). The Boö islands offer perhaps a similar example (p. 106), and finally the Togian islands are a

fine example of oscillating movements. According to Feuilleteau de Bruyn (1921), Rani and the islands along the east coast of Soepiori (Schouten islands, New Guinea) show remnants of an elevated barrier. His statement needs confirmation by a detailed investigation.

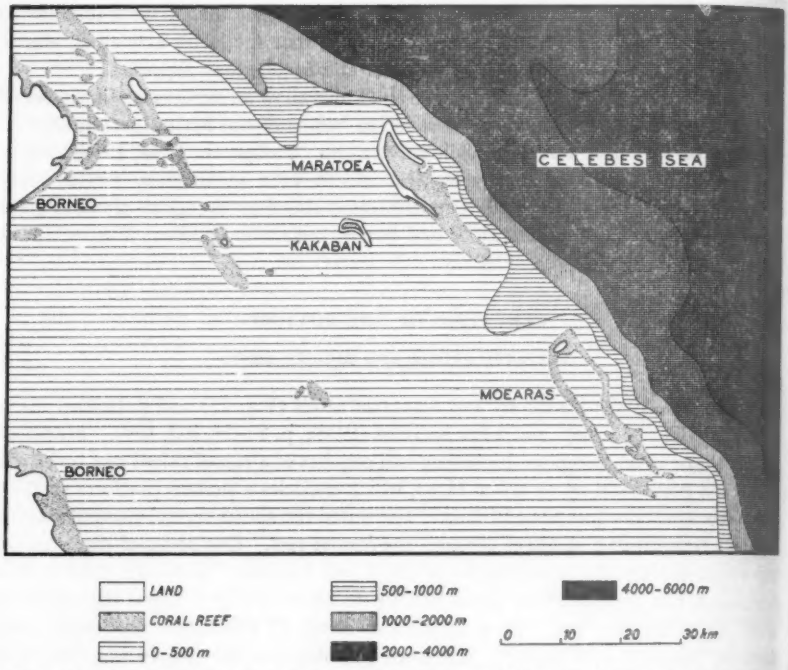

FIGURE 23.—*Bathymetrical chart of the region around Moearas atoll and the elevated atolls Maratoea and Kakaban, North East Borneo*

REEF TERRACES

Raised reef terraces or "karang" as the natives call them are a common feature especially in the Molluccas. Martin made some interesting remarks on elevated "karang" (1903; 1911), and Escher (1919) published a letter of Davis' giving theoretical considerations on the structure of raised reef terraces, which may be of interest to any one studying terraces *in situ*. The writer (1938a) compiled data about the height of elevated reefs in the surroundings of the Banda Sea. One of the finest examples is the island Kisar showing a reef cap of five vertically elevated terraces (Fig. 24, after Kuenen); the highest was 150 meters above sea level. In many islands the number of reef terraces is still greater—*e.g.*, 14 on Binongko, according to Kuenen.

As early as 1903 Martin clearly pointed out that the elevated reef terraces indicate vertical movements of the bottom and not changes of sea level. Earlier Martin (1896) had explained that basins like the Soeloe Sea, Celebes Sea, and Banda Sea

originated by downward movement of the bottom. He suggested that the elevation of the series of islands and the subsidence of adjacent regions giving origin to the deep-sea basins must have occurred simultaneously (1903, p. 286–288). The same trend of thought may be found in later theories of Verbeek, Molengraaff, Kuenen and Umbgrove. From all facts available it is evident that the present relief of deep

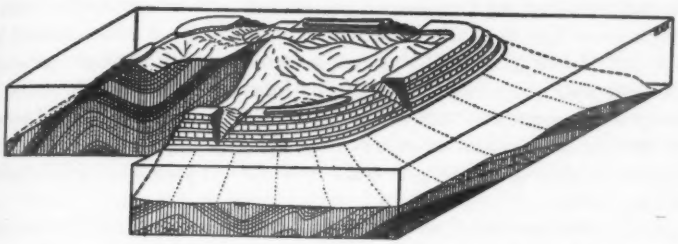

FIGURE 24.—*Schematic block diagram of the reef terraces on the island Kissar, northeast of Timor*
After Kuenen.

sea and island chains of the East Indies must have originated during the recent geological past. A geological argument may be found in two recent papers by the present author (1938a; 1938b). In his remarkable "geological interpretation of the bathymetrical results" of the SNELLIUS expedition Kuenen (1935) came to exactly the same conclusion. He also pointed out that these results are not compatible with Brouwer's hypothesis of a continuous and gradual folding and geanticlinal updoming of the island arcs and their gradual movement toward the "foreland." Martin argued as early as 1903 (p. 285, 486) that the reef caps indicate vertical movements and not folding of the substratum.

Up to now only one detailed investigation on elevated reef terraces has been carried out—*viz.*, by Kuenen (1933a, p. 55–60) on Binongko in the Toekang Besi group. The terraces are not all continuous around the island; on the contrary there seems a kind of irregular asymmetry. His careful measurements of 14 reef terraces along six sections across the island showed, however,

> "that Binongko has risen about 200 m as a solid block, at different periods but in a regular manner, without having been tilted. This would point to block-faulting rather than to folding of the substratum, a conclusion that also follows from the bathymetrical data."

A tilting and an accompanying asymmetrical development of elevated terraces on opposite coasts of an island are no proof of asymmetrical updoming. In the case of Lintea (Toekang Besi islands), perhaps the most convincing example of tilting, "the movements were principally, faulting and not undulatory" (Kuenen, 1933a, p. 95.) Moreover one should not forget that biological and other factors may prevent reef development along one side of an island, whereas simultaneously strong reef growth may occur on the opposite coast. Moreover, corrosion and even total destruction of elevated reef terraces may locally proceed faster than elsewhere; and creep and downsliding may cause inclination of reef terraces which are not primary. Therefore

we must be very cautious in drawing conclusions concerning tilting movements on the ground of negative evidence.

SUMMARY OF CONCLUSIONS

A coral reef may originate on a muddy bottom.

Sea currents bringing new supplies of oxygen are of vital importance for coral reefs. The penetration of light is greatly influenced by the quantity of silt suspended in the sea water, and the depth of the living reef is correlated with the light penetration.

East Indian reefs show very strikingly the influence of wind and waves. The morphology of the upper structure of the reef and the distribution of coral sand and debris as well as the localization of sand cay, shingle ramparts, and moat is controlled by the prevailing direction of monsoon winds or by an alternating system of land and sea wind.

The peculiar distribution of several typical coral faunas on small reefs is controlled by the same factors.

A recent negative shift of sea level too is an important factor in the formation of sand cay, shingle ramparts, and reef flat. Three successive levels—4–5 meters, 1½–2 meters, and 1½–1 meter—were observed.

The formation of shingle ramparts is highly favored by artificial destruction of the living reef carried out for economic purposes.

As a consequence of the wind-controlled deposition of coral sediment, conditions for coral growth are more favorable at the windward side of a reef than at its lee side. A coral reef grows more vigorously on the windward side because of the slight influence of sedimentation.

Coral boulders, so called negroheads, carried onto the reefs by powerful waves are common only in regions where either tropical disturbances (cyclones) or devastating waves caused by the eruption of a neighboring volcano occur.

The land-locked seas of the East Indies offer no favorable conditions for the origin of a lithothamnium ridge. Lithothamnia are flourishing on reefs that are open to the powerful surf on ocean coasts. On those coasts toothed reef edges have developed, characterized by narrow branched channels running nearly perpendicular to the reef edge. The rimmed pools so often seen in these reefs offer a phenomenon which seems not yet clear in detail.

The group of the Thousand Islands in the Java Sea and the Siboetoe reefs, North Borneo, offer excellent examples of the erosive action of sea currents, molding the shape of a whole group of coral reefs.

On geological evidence it is claimed that along limestone coasts in the tropics a solvent action of sea water exists, which seems limited between the tidal range.

Observations at Krakatoa and Oena-Oena volcanoes demonstrated that no extensive coral growth has developed because too many boulders and too much smaller detritus material is deposited along the submarine slopes. On other volcanic cones, however, flourishing reefs were observed.

In the formation of micro atolls both sedimentation and excavation are of importance.

In barrier reefs correlation exists between the depth of the lagoon and the distance from the barrier to the coast, if each area has a barrier that is entirely or practically closed and reaches as high as the level of the sea. The depth of a lagoon floor represents a balance between aggradation and removal of sediment. No evidence was found that solution and other degrading factors might produce a lagoon by excavation. Filling of lagoons is the normal feature in the East Indies. Probably in glacial times the lagoons were washed out more or less to a level related to the level of the glacial ocean.

Detailed considerations show that Pleistocene changes of sea level are of some importance to coral-reef problems, but that factor must not be overrated. East Indian reefs have been notably influenced either by Pleistocene climate or by mud control. Lowering of sea level may have caused active attack on exposed reefs and degradation of the lagoon floor. Rising sea level may favor development of the upper 100 meters or so of atoll and barrier reefs, but Glacial Control cannot explain the enormous thickness of so many East Indian atoll and barrier reefs.

Every East Indian atoll and barrier reef investigated in some detail shows that it gradually grew up on a subsiding bottom. Most of the atolls have grown on deeply submerged submarine ridges and plateaus from which they rise abruptly and steeply to the surface. In the Toekang-Besi group the bottom has subsided at least 1000 meters, at Taka Garlarang about 2000 meters.

Even in the elevated atolls of Maratoea and Kakaban the upward movement must have been preceded by subsidence.

Elevated terraces in some islands occur to considerable heights and point to block faulting rather than to the folding of the substratum.

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Institute of Mining, Delft, Holland

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DELINEATION OF PARALLEL FOLDS AND MEASUREMENT OF STRATIGRAPHIC DIMENSIONS

BY JOHN B. MERTIE, JR.

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ABSTRACT

The delineation of parallel folds in structural sections, and the extraction therefrom of stratigraphic information, has generally been done with considerable personal interpretation. If profiles must be drawn, or sections measured, from structural observations used in pairs, this is unavoidable; but superior results may be obtained if more than two observations are simultaneously utilized.

The first section of this paper is an exposition of the method of evolute and involutes, which is applicable if three or more observations are available, lying in or close to a profile plane that is normal to the strike of a series of folded rocks. Parallel curves, which in certain sections represent the traces of parallel stratigraphic surfaces, are necessarily involutes that may be generated from one or more evolutes. It is more practical to derive an evolute, and to construct from it a set of parallel curves,

than it is to draw such curves directly. Simple graphical methods are given for the construction of evolutes from different sets of structural data, and for the subsequent derivation of parallel curves. An examination of the resulting evolutes and involutes shows that most of them may be represented by the equation $y = ax^n$, if suitable values are assigned to the parameters a and n.

The second section of the paper is an exposition of methods that apply to the measurement of stratigraphic thickness, or other stratigraphic dimensions, if structural observations must be used in pairs. Four methods are discussed, which are known as the method of mean strikes and dips, the method of integrated trigonometric functions, the method of skew-line normals, and the method of integrated strikes and dips. The last named of these is a new method, which yields a mean value for the strike or dip, utilizing indirectly the concept of concentric arcs. A formula for mean dip (or mean strike) is derived, which has been computed for all values from 0° to 90°, at intervals of 5°. The results of this computation are given in a chart, which is used for the graphical computation of these values and for interpolation to less than 5°. The mean values of strike and dip that are thus obtained are substituted in any formula for stratigraphic dimensions that applies to a homoclinal sequence of rocks.

Under the topic of Errors and Differences, it is shown that the error resulting from the application of the method of evolute and involutes is small and is dependent mainly upon original errors in the determination of strike and dip. When observations are used in pairs, however, the resulting error may be much larger. If certain enumerated conditions are favorable, this error may be 10 per cent or less; but under unfavorable conditions, it may be 100 per cent or more.

INTRODUCTION

The delineation of folded strata and the measurement of their dimensions are problems with many aspects and ramifications. The geometrical character of the folding, real or assumed, must be deciphered or arbitrarily defined; the available stratigraphic data, or field observations, must then be considered; and, finally, suitable constructions and solutions must be devised. The derived results depend upon the fundamental definitions, upon the nature and amount of the stratigraphic data, and upon the types of solutions utilized.

An unlimited number of methods could be devised for representing parallel folds and for making stratigraphic measurements of the same. Some of these methods are highly involved and difficult of application; others are simple, but less accurate. One or more compromissary methods should therefore be used that are sufficiently accurate to meet geologic needs, and yet are easily applied. Moreover, a few such methods should be conventionalized for general application, so that the structural measurements and inferences made by one worker may be compared with those made by another. This is particularly true for stratigraphic thickness. In this paper the writer suggests some methods that may be worthy of general acceptance. Regardless, however, of whether these or some others are utilized, geologists should agree upon the most useful of the available methods and should work for their general adoption.

GENERAL CONSIDERATIONS

Parallel folds consist of folded strata bounded by stratigraphic surfaces that are essentially parallel. Truly parallel stratigraphic surfaces are rare, because it is

difficult to conceive of folding that has not caused a certain amount of differential stretching or compression of the beds. Moreover, such departures from parallelism may be accentuated by original differences in the thickness of strata and by other processes that were effective between the periods of deposition and deformation. Nevertheless, many folds approach the condition of parallelism so closely that, within limited intervals, this geometrical concept is warranted in making practical stratigraphic measurements. In fact, if the intervals of measurement can be made sufficiently small, the concept of homoclinal structure may properly be applied.

Besides the absence of true stratigraphic parallelism, many other factors operate to prevent the attainment of high accuracy in the study and measurement of sections. These include inaccuracy of original data, both geographic and geologic; paucity of structural observations or their absence at critical localities; and the geometrical complexity of folding. Therefore adequate accuracy requires that a sense of proportion be maintained, such that the shortcomings above mentioned may be realized, and that the published results shall be commensurate with these limitations. An indirectly measured thickness of folded rocks, for example, that is published as 318.6 feet is absurd. Probably the figure 318 is unwarranted, and should be changed to 320; and possibly 300 feet is the nearest justified approximation.

This paper consists of two parts, of which the first is devoted primarily to the preparation of geologic profiles. From suitable profiles, however, the stratigraphic thickness may be scaled with considerable accuracy. Therefore good profiles, if they can be constructed, serve both for structural delineation and for stratigraphic measurements. A geologic profile is commonly drawn to show the true curvature and stratigraphic thickness of a set of folded beds. The strike is constant in a horizontal cylindrical fold, for which reason the resulting profile will lie in a vertical plane; the same is true for particular sections in certain types of quaquaversal folds. In a pitching cylindrical fold, the strike changes along any traverse lying in a plane normal to the axis of the fold; yet an oblique plane profile is still feasible if the pitch of the fold can be determined. Generally, however, if the strike and dip vary from point to point, the horizontal trace of the profile plane will be a curved line, and the required profile will lie in a curved surface. Such profiles are impracticable and ordinarily are not attempted.

The general method of evolute and involutes is devised to show in plane profile the structure and thickness of beds in parallel folds. The traverse must therefore be made in a profile plane that is normal to the stratigraphic surfaces and to the axis of the fold. The method utilizes three or more structural observations, of varying dip but constant strike, that lie along or close to a straight line which is the horizontal trace of a linear traverse normal to the strike. If some of the sites of observations do not lie within the specified profile plane, or if the projected line of traverse is not exactly normal to the strike, the observations may by various methods be projected into the profile plane with slight error. Owing to relief, the actual traverse will commonly be a curved line in the plane of the profile.

The general method of evolute and involutes makes no assumption regarding the curvature of parallel folds; on the contrary, the true curvature is deduced from the dips of the beds. Where it can be used, this method makes the best possible use of

the available data, gives the greatest obtainable accuracy, and may be carried out entirely by a simple geometrical technique. Neither this nor any other other method can be used to prepare profiles of the kind specified, in planes oblique to the strike of the rocks, even if the strike is constant, because in such profiles the traces of the beds will be nonparallel curves which will show neither the true curvature nor the stratigraphic thickness. With a constant strike, however, the observations may be projected into some other plane that permits the construction of a satisfactory profile.

The second part of this paper considers the measurement of stratigraphic dimensions, where suitable profiles are difficult or impossible to construct. Such conditions may arise from several causes. The traverse may be oblique to the strike of the rocks; the sites of the observations may be so scattered on a map that no three or more of them lie in or close to the required profile plane; or the strike and dip may vary erratically from point to point. Such data, though unsuitable for the preparation of accurate profiles, can be used in the measurement of stratigraphic thickness or other stratigraphic dimensions. Any practical method devised for this purpose, however, will be restricted to the utilization of structural observations in pairs and will of necessity be empirical. The method proposed herewith is based on analysis rather than geometry, but geometrical methods are given for its application.

METHOD OF EVOLUTE AND INVOLUTES

The definition already given for parallel folds is strictly accurate, but it is a three-dimensional concept that cannot be practically applied. In actual practice, parallel folds are best studied in transverse sections, and preferably in sections that show the traces of the stratigraphic surfaces as parallel curves. What are parallel curves? If a straight line rolls without slipping on some curved line, both being in the same plane, any point on the straight line describes a curve which is called an involute. The fixed, or generating, curve is called an evolute. Obviously the rolling straight line describes an infinite number of involutes. From the manner of their formation, an evolute and its involutes possess certain distinctive geometrical properties: (1) The rolling straight line is everywhere tangent to the evolute and intersects all the involutes at right angles; conversely, any normal to an involute is tangent to its evolute. (2) Two involutes of the same evolute intercept a constant distance on all normals. Therefore, being separated by constant distances, involutes are known as parallel curves. Concentric arcs are involutes about a point.

If it be required that the traces of parallel surfaces shall be parallel curves, which will show both the true curvature of the beds and their stratigraphic thickness, the profile must be constructed normal to the stratigraphic surfaces and to the axis of the fold. Over an extended interval this might require that the profile should be a curved or warped surface, but, in actual practice, either the position of the section is so chosen, or the interval is taken so small, that a plane profile can be drawn to illustrate the salient structural features. In Figures 1, 2, 4–10, and 12, plane vertical profiles are shown of cylindrical parallel folds, wherein the strike is constant. Each profile lies in a plane that is normal to the stratigraphic surfaces, normal to the horizontal axis of the fold, and therefore normal to the strike of the rocks. The intersection of the profile plane with the plane of the horizon, designated as AB, forms the base of the figures.

For simplicity in a theoretical presentation, the traverse, which owing to relief may be a curved line in the plane of the profile, is not shown; but in practice, the tangents to the evolute will start from stations on the actual traverse. The relief will also be shown in the interpolation charts, exemplified by Figures 3 and 11; and here the normals to the dips should be extended downward (or upward) to meet the base

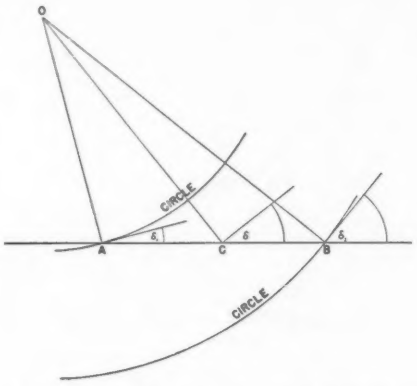

FIGURE 1.—*Profile showing traces of stratigraphic surfaces, depicted as concentric arcs*

line AB. It should also be mentioned, in connection with cylindrical folds, that no restriction is placed on the character of the parallel plane curves that guide the generatrix of the cylinders.

Figure 1 illustrates a vertical plane profile where two dips, δ_1 and δ_2, are plotted respectively at A and B, the initial and terminal points of a traverse. At these end points, normals to the dips are drawn which intersect at O; and, from O as a center, circular arcs are drawn through A and B. The distance between these arcs, measured along one of the normals, is the stratigraphic thickness, as defined by Hewett (1920, p. 367–385). In this construction it will be noticed that all intermediate dips lying between A and B, such as δ, are rigidly defined, regardless of what values they may actually have in nature. Therefore, in utilizing this construction, it is necessary to consider adjacent observations in pairs, thus requiring $n-1$ constructions for n observations. Actually, this method was designed more for the measurement of stratigraphic thickness in suitable sections than for the constuction of profiles. It also has important indirect applications, of which more will be said in the second section of this paper.

The character of parallel curves is shown in Figure 2. Here, as in the preceding figure, two dips are plotted at A and B, the end points of a traverse. An intermediate dip, δ, is also shown, whose magnitude is not determined by δ_1 and δ_2, as it is in the concentric structure. In this construction, normals drawn to the traces of the stratigraphic surfaces at A, B, and C do not meet in a point. Instead they form a system of lines that are tangent to an evolute, and in fact constitute its envelope. The construction of this evolute is later described. Now if a large number of pins are inserted in the paper along this evolute, and if a strong thread is anchored at the

last of these pins, the other end of the thread may be unwound in such a manner as to represent a straight line rolling upon the evolute. Any selected point on this thread will occupy successively many positions, the loci of which will describe a new curve called the involute. Obviously an unlimited number of involutes can be

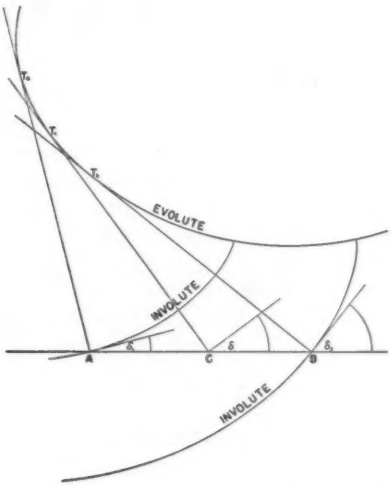

FIGURE 2.—*Profile showing traces of stratigraphic surfaces, depicted as involutes*

drawn, depending upon the number of points on the thread that are selected. Two such involutes are shown in Figure 2, and the distance between them, as measured along the unwinding thread, is defined as the stratigraphic thickness. In actual practice, the involutes are drawn by inserting the point of a pencil in loops along the thread and unwinding the thread in the manner described.

The value of this construction and of the resulting definition of stratigraphic thickness lies in the fact that any number of observations between A and B may be utilized in constructing a profile; and the verisimilitude of the resulting profile increases directly as the number of intermediate observations. Thus, in a straight stretch of a canyon, where a series of rocks is continuously or intermittently exposed, a large number of structural observations can be utilized, and the involutes that can be drawn from these observations will show closely in profile the true nature of the folding. The structure of folded rocks can be more accurately shown by this method than by any other known to the writer.

The construction of involutes, if the evolute is known, has been shown to be little more difficult than the construction of concentric circles. It remains to be demonstrated that the evolute can likewise be simply constructed. If in Figure 2 a number of intermediate dips had been plotted between A and B, and the normals to these traces had been drawn, these normals would constitute a system of tangents to the evolute and would delimit an envelope from which the evolute could readily be

sketched. The successful construction of the evolute, however, depends upon the construction of many normals to the traces of the stratigraphic surfaces, preferably so distributed that their starting points are equally spaced between A and B. This distribution can be attained, even if only one or two intermediate observations of dip

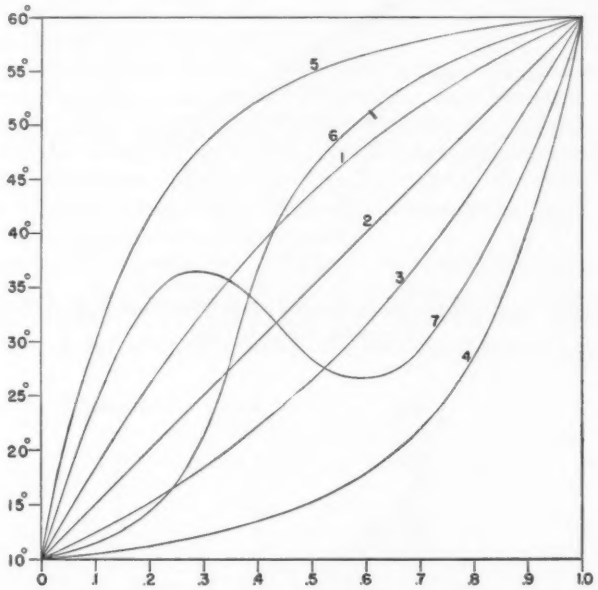

FIGURE 3.—*Certain modes of variation in dip, between initial and terminal points of a traverse*

are available, in the following manner. In Figure 3, let the horizontal trace of the traverse be represented by a straight line, or axis of X, divided into 10 equally spaced intervals. Assume also that the least favorable condition exists namely, that only one observation of dip is available between the end points of the traverse. Consider any one of the curves shown in Figure 3, say curve 4. If at some point along the traverse, corresponding to the site of the intermediate observation, the dip in degrees is plotted as an ordinate, two end points and one intermediate point will be available, through which, by the principle of minimum curvature, curve 4 may be sketched. The position of curve 4 could of course be more exactly located, if several intermediate values of the dip were known; but, even with a single intermediate point, a curve results that much more closely represents the truth than if a straight line, such as curve 2, had been drawn between the two end points without reference to any intermediate point. Curve 4 therefore represents all the information available as to the manner in which the dip changes between the initial and terminal points of the traverse. Now scale the ordinates of curve 4, corresponding to the abscissae .1, .2, .3, etc. These ordinates are the values of the dips required to draw the system

of normals which delimit the envelope that determines the position of the required evolute. The evolute and involutes that are constructed from curve 4 are shown in Figure 7.

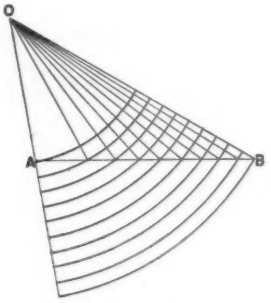

FIGURE 4.—*Profile showing structure that results from concept of concentric arcs illustrated by curve 1 in Figure 3*

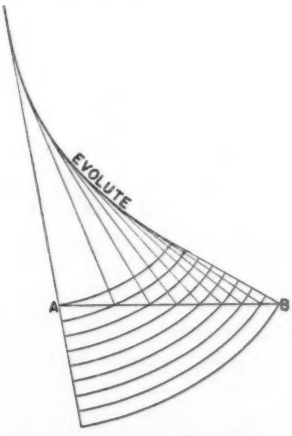

FIGURE 5.—*Profile showing structure that results from linear mode of variation in dip illustrated by curve 2 in Figure 3*

Seven curves, including curve 4, are shown in Figure 3. These represent different variations in dip that may exist between the two ends of a traverse, *A* and *B*, where the initial and terminal dips are respectively 10° and 60°. These two particular dips have no special significance but were selected merely to illustrate a general principle. Curve 1 represents the manner of variation in dip if a profile is constructed according to the principle of concentric arcs. A profile of the resulting structure is shown in Figure 4. Curve 2 represents the linear mode of variation in dip that is sometimes assumed to exist between two terminal dips, where no intermediate observations are

known. By scaling the ordinates from curve 2, corresponding to selected intermediate positions on the X axis, and by constructing therefrom a system of normals at these intermediate points, the structure shown in Figure 5 results. The other curves, numbered 3, 4, 5, 6, and 7, are similarly drawn and illustrate other modes of variation in dip that may exist between the end values of 10° and 60°. The evolutes and involutes resulting from such variations are shown in the profiles illustrated respectively in Figures 6, 7, 8, 9, and 10.

An infinite number of curves similar to those shown in Figure 3 might conceivably represent modes of variation in dip between 10° and 60°. If no intermediate values have been observed, either curve 1 or 2 will be a reasonable one to use, though curve 1 would probably be selected by most geologists. If intermediate observations are available, however, a proper variation curve (or interpolation curve) can be constructed, from which the traces of the stratigraphic surfaces can be drawn, and the stratigraphic thickness scaled, with great precision.

The stratigraphic thicknesses shown in Figures 4 to 10, inclusive, are worthy of special examination. If the distances AB in all these drawings are taken as equal in length, and if the stratigraphic thickness scaled from Figure 4 is taken as unity, the thicknesses shown in the other six drawings will have the following proportional values:

Figure no.	Curve no.	Ratio
4	1	1.00
5	2	.91
6	3	.78
7	4	.58
8	5	1.19
9	6	.97
10	7	8.6

Thus the stratigraphic thickness obtained from Figure 8 is more than twice that obtained from Figure 7; and other more extreme modes of variation in dip, between the terminal values of 10° and 60°, would yield still greater differences in thickness. These drawings therefore demonstrate the following facts: (1) Stratigraphic thickness computed from dips at the two ends of a traverse is subject to large but indeterminate errors; (2) these errors increase with the distance between the end points, A and B; (3) they increase with the difference between the terminal dips, δ_1 and δ_2; and (4) they can largely be eliminated if intermediate observations are available and are utilized in the general method of evolute and involutes.

In Figures 4 to 10, inclusive, structures have been considered in which the rocks dipped throughout the traverse in the same direction. The method of evolute and involutes is by no means restricted to the derivation of such structures. Curve 8, in Figure 11, shows a mode of variation such that the dip changes from 80° in one direction, say northward, to 40° southward. The evolute and involutes resulting from this type of variation are shown in Figure 12. In reality, the evolute of Figure 12 is a parabola of higher order that is represented by the equation $y = \sqrt{10}x^4$ or $y^2 = 10x^8$. The involutes, or traces of the bedding surfaces, are higher-plane curves that resemble parabolas of higher order. The general conclusion is that any set of observations in parallel folds, consisting of constant or nearly constant strikes,

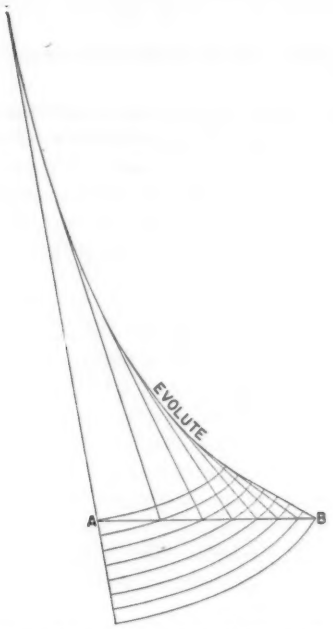

FIGURE 6.—*Profile showing structure that results from mode of variation in dip illustrated by curve 3 in Figure 3*

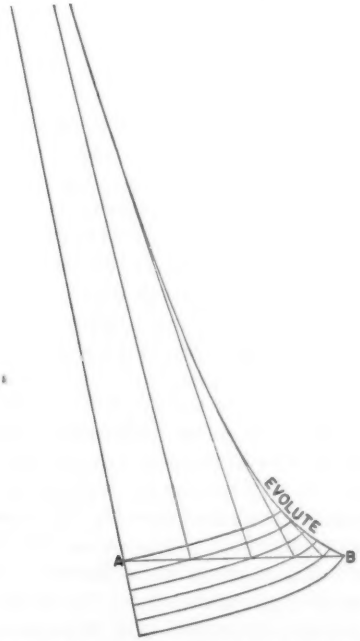

FIGURE 7.—*Profile showing structure that results from mode of variation in dip illustrated by curve 4 in Figure 3*

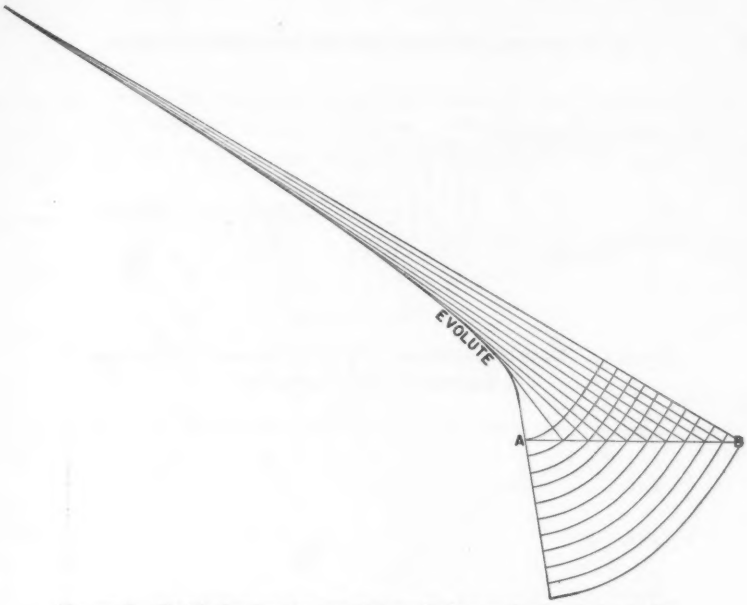

FIGURE 8.—*Profile showing structure that results from mode of variation in dip illustrated by curve 5 in Figure 3*

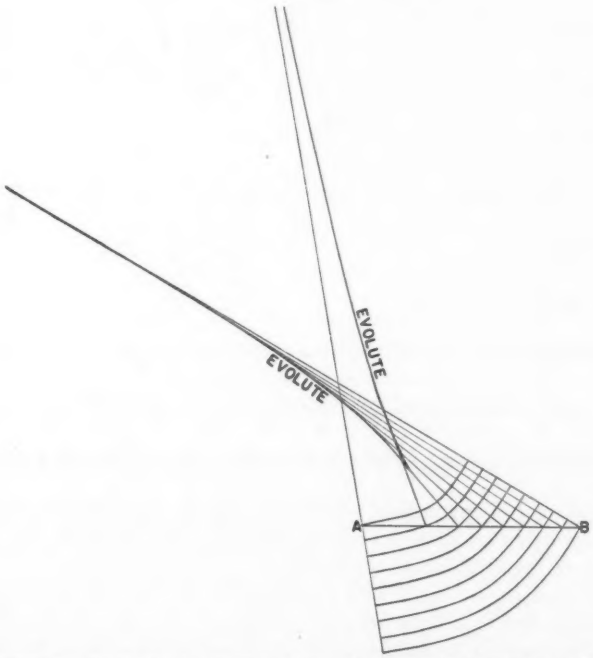

FIGURE 9.—*Profile showing structure that results from mode of variation in dip illustrated by curve 6 in Figure 3*

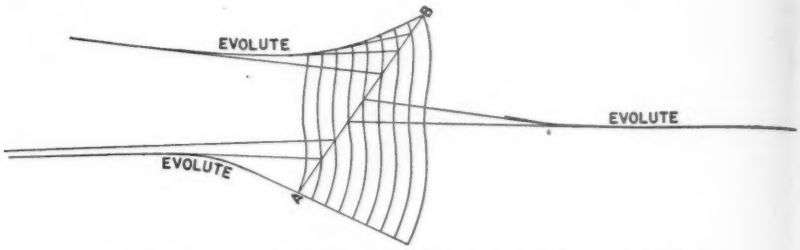

FIGURE 10.—*Profile showing structure that results from mode of variation in dip illustrated by curve 7 in Figure 3*

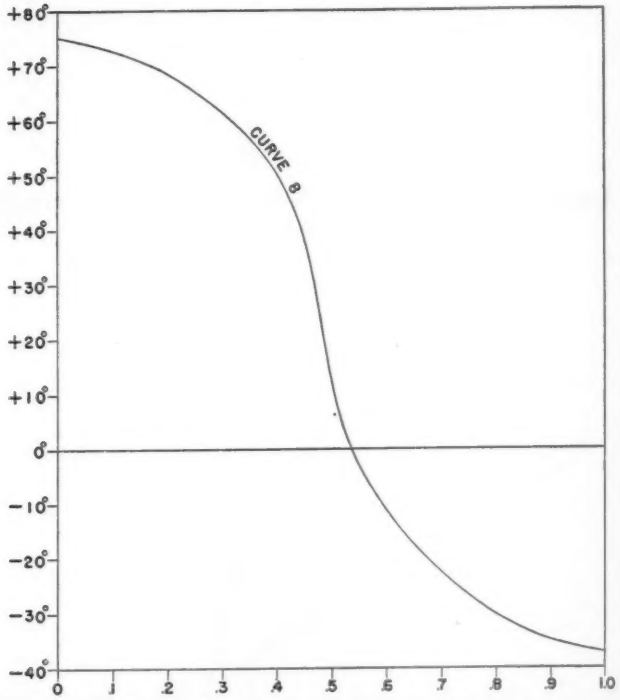

FIGURE 11.—*Mode of variation in dip, showing a reversal from north to south*

and dips that vary in any manner whatsoever, may be analyzed and resolved by the method of evolute and involutes into profiles that constitute the best possible interpretation of the available structural data.

A word of caution is needed with regard to the construction of evolutes. It has already been shown that these are sketched from an envelope produced by a set of normals to the traces of the bedding surfaces, drawn from successive sites of structural

observations. These normals must be carefully drawn if the resulting envelope is to represent accurately the locus of the evolute. A diagram such as Figure 3 may be constructed on a scale such that the ordinates can be scaled to a tenth or a twentieth

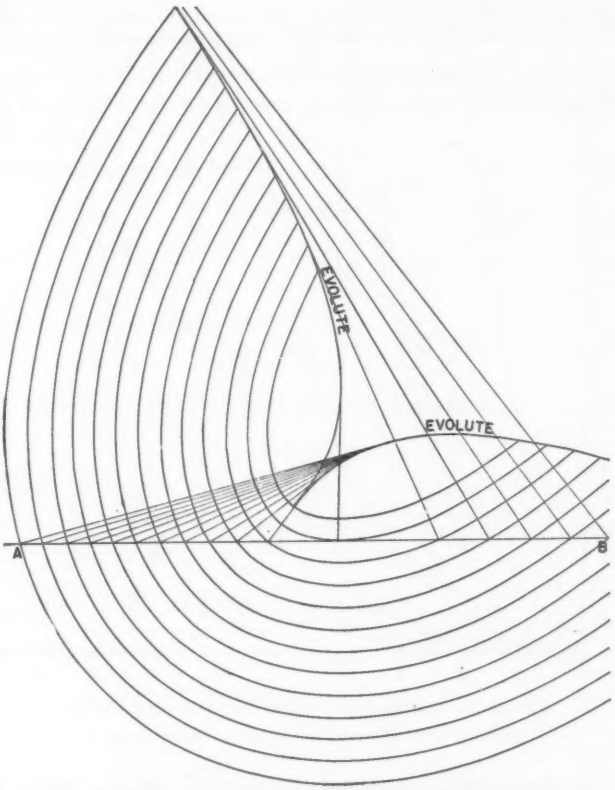

FIGURE 12.—*Profile showing structure that results from mode of variation in dip illustrated by curve 8 in Figure 11*
The evolute is represented by the equation $y = \sqrt{10}\, x^{3/2}$.

of a degree; and the corresponding normals, as in Figures 4–10 and 12, must be laid off at least as accurately as the ordinates were read. For this reason, an ordinary large protractor reading to half degrees or quarter degrees is too inexact; instead, a vernier protractor, reading to 3 minutes of an arc or less, should be used. With these precautions, no difficulty will be experienced in constructing evolutes that correspond exactly with the true structures. Much less care is required in drawing the involutes, the principal requirement being the use of a non-stretching thread.

ANALYSIS

The similarity of the evolutes shown in Figures 5–10, and 12, is striking; and the query naturally arises whether they are so related that they can be represented by a general algebraic formula. The exact equations of these evolutes would doubtless

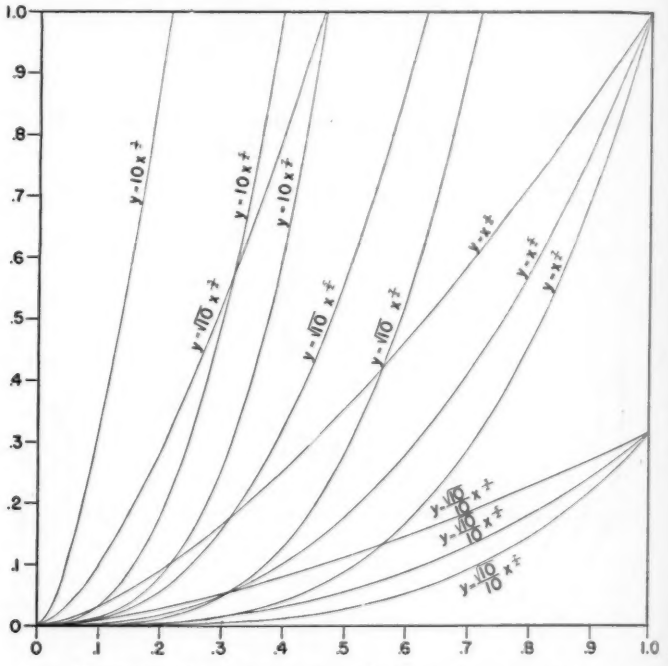

FIGURE 13.—*Various curves representing the equation* $y = ax^n$ *with different values assigned to the parameters a and n*

prove to be highly complex, as was shown by the writer (Mertie, 1940, p. 1116) in an earlier publication. But their forms suggest that they can be represented approximately by the equation $y = ax^n$, if suitable values are assigned to the parameters a and n. The semicubical parabola is represented by the equation $y = ax^{\frac{3}{2}}$, or $y^2 = a^2x^3$; and parabolas of higher order, symmetrical to the axis of X, are produced if n is an improper fraction, with an odd numerator and an even denominator. Similar curves, symmetrical to the axis of Y, are produced if n is a proper fraction, with an even numerator and an odd denominator. Figure 13 shows the positive halves of 12 such curves, where a equals 10, $\sqrt{10}$, 1, and $\frac{\sqrt{10}}{10}$, and n equals $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$. Scrutiny of these curves will show the influence of differing values of a and n and will prove the feasibility of matching approximately any of the desired evolutes by means of the formula $y = ax^n$.

The parabola is an involute of the semicubical parabola, but curves drawn parallel to the parabola, or parallel to the involutes of parabolas of higher order, are not parabolas. All these involutes, however, resemble closely the parabolas of higher order and can be matched approximately by the equation $y = ax^n$, where n is a proper fraction with an odd numerator and an even denominator. For similar curves, symmetrical to the Y axis, the exponent n will be an improper fraction, with an even numerator and an odd denominator.

The true equations of the involutes may possibly be required. Assuming that the evolute can be represented by a parabola of higher order, the following method of derivation may be used:

Let the equation of the evolute be

$$y = ax^n \tag{1}$$

Differentiating, we have

$$y^1 = nax^{n-1} \tag{2}$$

The equation of any straight line is

$$y - y_0 = y^1(x - x_0)$$

In order that this straight line shall be tangent to the evolute

$$y = ax^n,$$

its equation must be written as

$$y - y_0 = nax^{n-1}(x - x_0)$$

or

$$nax^n - nax_0x^{n-1} - y + y_0 = 0 \tag{3}$$

Differentiating (3) with regard to x, we have,

$$n^2ax^{n-1} - n(n-1)ax_0x^{n-2} - y^1 = 0$$

or

$$x_0 = \frac{n^2ax^{n-1} - y'}{n(n-1)ax^{n-2}} = \frac{n}{n-1}x - \frac{x^{2-n}y'}{na(n-1)} \tag{4}$$

Substituting this value of x_0 in (3), we get,

$$nax^n - \frac{n^2a^2x^{2n-2} + nax^{n-1}y'}{n(n-1)ax^{n-2}} - y + y_0 = 0$$

$$nax^n - \frac{n^2a}{n-1}x^n + \frac{1}{n-1}xy' - y + y_0 = 0$$

whence

$$y_0 = \frac{na}{n-1}x^n - \frac{1}{n-1}xy' + y \tag{5}$$

But these values of x_0 and y_0 must also satisfy the original equation. Therefore the differential equation of all the tangents to $y = ax^n$ is

$$\frac{na}{n-1}x^n - \frac{1}{n-1}xy' + y = a\left[\frac{n}{n-1}x - \frac{x^{2-n}y'}{na(n-1)}\right]^n \tag{6}$$

The family of involutes are the orthogonal trajectories of this family of tangents. Therefore, substituting $\frac{1}{y'}$ for y' in (6) we obtain the differential equation of all the involutes to the curve $y = ax^n$, as follows:

$$\frac{na}{n-1}x^n + \frac{1}{n-1}\cdot\frac{x}{y'} + y = a\left[\frac{n}{n-1}x + \frac{1}{na(n-1)}\cdot\frac{x^{2-n}}{y'}\right]^n$$

If suitable values are substituted for the parameters a and n, the solution of the resulting differential equation will give the true equation of the family of involutes to any parabola of higher order. The quadrature of such equations, however, will be difficult and may indeed be impossible. Two alternatives therefore exist. If an algebraic record of the profile is desired, either the equation of the evolute or the unsolved differential equation of the involutes may have to serve.

METHOD OF OBSERVATIONS BY PAIRS

In tilted or folded rocks, let the significant structural data be as follows:

Let s = the distance between any two points, A and B, in a stratigraphic sequence.
h = the orthographic projection of s onto the plane of the horizon. This is the plane-table distance between A and B.
e = the difference in altitude between points A and B, such that $e = (s^2 - h^2)^{\frac{1}{2}}$.
σ = the vertical angle which a line connecting A and B makes with the plane of the horizon.
δ = the angle of dip of a plane tangent to a stratigraphic surface at a station point.
α = the horizontal angle between h and the strike of a plane tangent to a stratigraphic surface.
t = the stratigraphic thickness.

The following well-known formulae for stratigraphic thickness apply to a homoclinal sequence of rocks:

$$t = s(\sin\alpha \sin\delta \cos\sigma \pm \cos\delta \sin\sigma) \tag{7}$$
$$t = h(\sin\alpha \sin\delta \pm \cos\delta \tan\sigma) \tag{8}$$
$$t = e(\sin\alpha \sin\delta \cot\sigma \pm \cos\delta) \tag{9}$$
$$t = h \sin\alpha \sin\delta \pm e\cos\delta \tag{10}$$
$$t = h \sin\alpha \sin\delta \pm (s^2 - h^2)^{\frac{1}{2}} \cos\delta \tag{11}$$
$$t = (s^2 - e^2)^{\frac{1}{2}} \sin\alpha \sin\delta \pm e\cos\delta \tag{12}$$

Two of the four variables s, h, e, and σ are used in each formula, and any one formula can be simply transformed to any of the others. Similar formulae are available for depth to a stratum, distance to a stratum, and other stratigraphic dimensions.

The simplest method of applying these formulae to folded rocks, when the strike and dip are different at the two stations A and B, is to insert for δ the mean value of δ_1 and δ_2, the dips at the two station points; and for α the mean value of the two corresponding horizontal angles α_1 and α_2. This, which may be called the method of

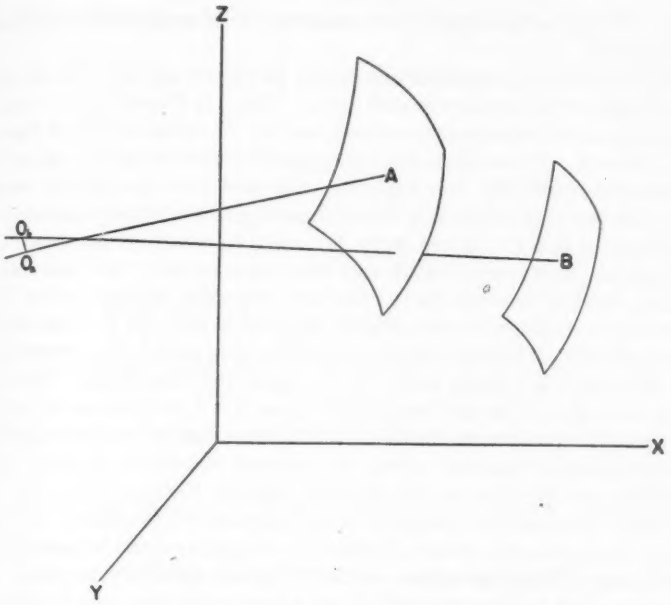

FIGURE 14.—*Stratigraphic surfaces and skew line normals illustrating one method for determining stratigraphic thickness*

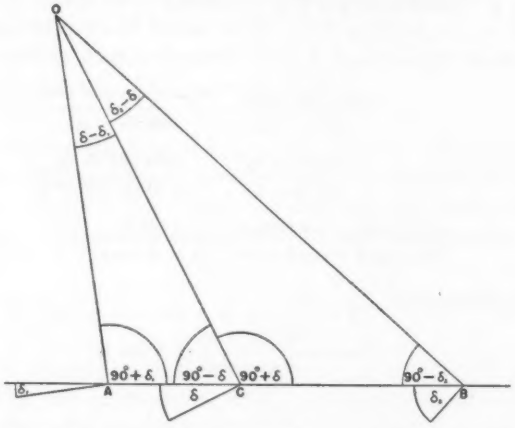

FIGURE 15.—*Relationships between dips, in a profile showing concentric arcs*

mean strikes and dips, was used by Dr. Charles K. Swartz, in his work in western Maryland 40 years ago, and later was taught by him to his students. Professor Swartz used the homoclinal formula $t = h \sin \alpha \sin \delta \pm e \cos \delta$. For certain ob-

servations, this method is entirely satisfactory, but for other observations the results can be improved.

The Hewett method of concentric arcs cannot be directly applied, if the strike and dip are different at the two sites of observation. Thus, in Figure 14, let A and B be station points on two stratigraphic surfaces, and let the strike and dip at these two points be different. If normals to the stratigraphic surfaces be constructed at A and B, and extended indefinitely, they will prove to be skew lines that nowhere meet one another. Hence no concentric arcs, drawn according to the Hewett method, can be passed through A and B. At two particular points, however, designated as O_a and O_b, a line may be drawn connecting the skew lines that is normal to both and measures the shortest distance between them. Hence a reasonable analogy to the Hewett method would be to define the stratigraphic thickness as $O_bB - O_aA$. The technique of the determination of thickness by this method has been given by the writer (Mertie, 1944, p. 1376–1386) in a recent paper, but its application is laborious. One way in which the method could be used would be to make $(171)^2$ or 29,241 solutions, which would represent all possible combinations of strikes and dips, at intervals of 5 degrees.

Another method by which the concept of concentric arcs can be indirectly utilized was developed several years ago by the writer (Mertie, 1940, p. 1127–1132). This may be called the method of integrated mean trigonometric functions. It is easily applied but makes use of a numerical solution. Six graphs would be needed to give the method a graphic interpretation, and this is the principal objection to it.

A fourth method is now proposed by the writer, which also uses indirectly the concept of concentric arcs in homoclinal formulae. Referring to Figure 15, let the dips at stations A and B be respectively δ_1 and δ_2; and let any intermediate dip be designated as δ. The distance AB is considered to be a unit distance, such that $AB = 1$, $AC = s$ and $CB = 1-s$. It is desired to find the manner in which δ varies, as the point C moves from A to B. From the figure, we have:

$$\frac{s \sin (90° \pm \delta_1)}{\sin (\delta - \delta_1)} = \frac{(1 - s) \sin (90° \mp \delta_2)}{\sin (\delta_2 - \delta_1)}$$

$$\frac{\sin (\delta - \delta_1)}{\sin (\delta_2 - \delta_1)} = \frac{s \sin (90° \pm \delta_1)}{(1 - s) \sin (90° \mp \delta_2)}$$

$$\frac{\sin \delta \cos \delta_1 - \cos \delta \sin \delta_1}{\sin \delta_2 \cos \delta - \cos \delta_2 \sin \delta} = \frac{s \cos \delta_1}{(1 - s) \cos \delta_2}$$

which may be reduced to

$$\tan \delta = \frac{\sin (\delta_2 - \delta_1)}{\cos \delta_1 \cos \delta_2} \cdot s + \tan \delta_1$$

Hence

$$\delta = \arctan (ks + g) \tag{13}$$

where

$$k = \frac{\sin (\delta_2 - \delta_1)}{\cos \delta_1 \cos \delta_2} \quad \text{and} \quad g = \tan \delta_1$$

The average value of δ for the unit distance $s = 1$, is as follows:

$$\bar{\delta} = \int_0^1 \text{arc tan } (ks + g)\, ds$$

Let

$$ks + g = x$$

$$k\, ds = dx$$

$$ds = \frac{1}{k}\, dx$$

Also, if $s = 1$, $x = k + g$; and if $s = 0$, $x = g$

$$\therefore \bar{\delta} = \int_0^1 \text{arc tan } (ks + g)\, ds = \frac{1}{k}\int_g^{k+g} \text{arc tan } x\, dx$$

$$\bar{\delta} = \frac{1}{k}[x \text{ arc tan } x - \tfrac{1}{2}\log_e(1 + x^2)]_g^{k+g}$$

$$\bar{\delta} = \frac{1}{k}[(k + g) \text{ arc tan } (k + g) - \tfrac{1}{2}\log_e\{1 + (k + g)^2\} - g \text{ arc tan } g + \tfrac{1}{2}\log_e(1 + g^2)]$$

$$\bar{\delta} = \frac{1}{k}[\tan \delta_2 \text{ arc tan } (\tan \delta_2) - \tfrac{1}{2}\log_e(1 + \tan^2 \delta_2) - \tan \delta_1 \text{ arc tan } (\tan \delta_1) + \tfrac{1}{2}\log_e(1 + \tan^2 \delta_1)]$$

$$\bar{\delta} = \frac{1}{k}[\delta_2 \tan \delta_2 - \tfrac{1}{2}\log_e(1 + \tan^2 \delta_2) - \delta_1 \tan \delta_1 + \tfrac{1}{2}\log_e(1 + \tan^2 \delta_1)]$$

$$\bar{\delta} = \frac{\cos \delta_1 \cos \delta_2}{\sin (\delta_2 - \delta_1)}\left[\delta_2 \tan \delta_2 - \delta_1 \tan \delta_1 + \tfrac{1}{2}\log_e\left(\frac{1 + \tan^2 \delta_1}{1 + \tan^2 \delta_2}\right)\right]$$

$$\bar{\delta} = \frac{\cos \delta_1 \cos \delta_2}{\sin (\delta_2 - \delta_1)}\left[\delta_2 \tan \delta_2 - \delta_1 \tan \delta_1 + \log_e\left(\frac{\cos \delta_2}{\cos \delta_1}\right)\right] \tag{14}$$

The mean dip, $\bar{\delta}$, is the mean value of δ, if the two terminal values δ_1 and δ_2 are considered to be related to one another by the concept of concentric arcs. This mean value, $\bar{\delta}$, is substituted for δ in any formula that applies to the measurement of stratigraphic dimensions in a homoclinal series of rocks. The corresponding formula for the horizontal angle is

$$\bar{\alpha} = \frac{\cos \alpha_1 \cos \alpha_2}{\sin (\alpha_2 - \alpha_1)}\left[\alpha_2 \tan \alpha_2 - \alpha_1 \tan \alpha_1 + \log_e\left(\frac{\cos \alpha_2}{\cos \alpha_1}\right)\right] \tag{15}$$

Formulae 14 and 15 appear formidable and are in fact laborious of solution. To obviate this difficulty, (14) has been computed for all possible combinations of dip, at intervals of 5 degrees. For graphic interpolation to 1 degree, a nomogram relating all values of δ, δ_1, and δ_2 would have been the best solution, but the formula contains several functions of δ_1 and δ_2, so that a nomogram would be difficult to construct. Instead, a chart has been prepared, as shown in Figure 16, which gives the positive correction that must be added to $\frac{\delta_1 + \delta_2}{2}$ to yield the corresponding value of $\bar{\delta}$.

This chart resembles a nomogram but is not strictly so, although it is used in a similar manner, as follows. The values of δ_1 and δ_2 are traced to an intersection in the curvilinear network. Through this intersection, a horizontal line is passed,

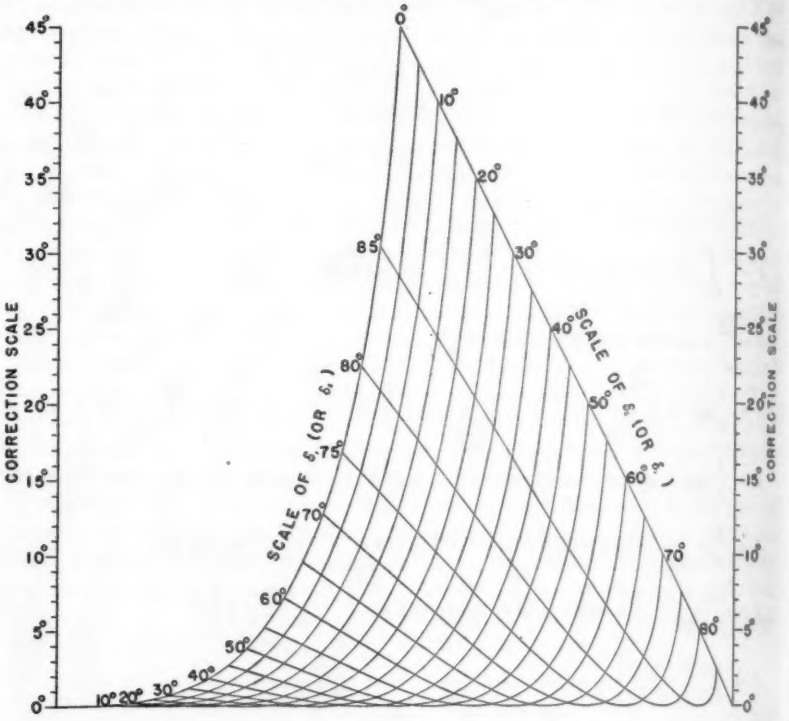

FIGURE 16.—*Chart for the graphic measurement of correction to be applied to mean strike or mean dip*

using for this purpose a scale or a straight-line index. The desired positive correction to $\frac{\delta_1 + \delta_2}{2}$ is read on either vertical scale, both of which are calibrated merely to facilitate the proper placement of a horizontal index line. Thus if δ_1 and δ_2 have values respectively of 20° and 60°, a horizontal line passed through the intersection of the curved lines corresponding to these values will read approximately 4.2° on either of the vertical scales. Hence the value of $\bar{\delta}$ will be $\bar{\delta} = \frac{20° + 60°}{2} + 4.2° = 44.2°$. This value is then applied in any of the homoclinal formulae (7)–(12); and the same procedure is used for obtaining $\bar{\alpha}$. Nomograms for the graphic solution of the homoclinal formulae for stratigraphic thickness and depth to a stratum, have been published by the writer (Mertie, 1922, p. 39–52).

Figure 16 serves one other useful purpose. Strikes and dips can not ordinarily be read closer than 1 degree, and in some circumstances they are not read closer than

5 degrees. Therefore, if values of δ_1 and δ_2 lead to some intersection in the curvilinear network that demands a correction of 1 or 2 degrees, the correction will not ordinarily be worth making. Instead, the mean dip may be taken merely as $\frac{\delta_1 + \delta_2}{2}$ and substituted directly in the homoclinal formula. The same procedure applies to two values of α_1 and α_2. Thus the chart not only gives the correction to $\frac{\delta_1 + \delta_2}{2}$ or $\frac{\alpha_1 + \alpha_2}{2}$, required for homoclinal formulae, but also indicates whether such a correction is warranted.

ERRORS AND DIFFERENCES

A homoclinal sequence of rocks presents the most favorable condition for the actual determination of possible error in the computation of stratigraphic dimensions. Barring irregularities of bedding in such a structure, inaccuracies in the answer result mainly from original errors in the determination of strike and dip. The effects of these observational errors can be mathematically determined; and as such errors are made in all kinds of structures, it seems desirable to evaluate their effects. The results, as later shown, are particularly applicable to the method of evolute and involutes.

Let it be desired to determine the error in stratigraphic thickness, in a homoclinal series of rocks, resulting from certain original errors of observation. By the use of a plane table, or a transit, the geographic measurements h and e can be so accurately made that their errors are inconsequential. The variables α and δ, however, are inherently subject to large relative errors. Consider the homoclinal formula $t = h \sin \alpha \sin \delta \pm e \cos \delta$ (10). For the resulting error in thickness, the total differential of t is required, regarding h and e as constants, and α and δ as variables.

$$dt = \frac{\partial t}{\partial \alpha} d\alpha + \frac{\partial t}{\partial \delta} d\delta$$

$$\frac{\partial t}{\partial \alpha} = h \cos \alpha \sin \delta$$

$$\frac{\partial t}{\partial \delta} = h \sin \alpha \cos \delta \mp e \sin \delta$$

$$\therefore dt = (h \cos \alpha \sin \delta)\, d\alpha + (h \sin \alpha \cos \delta \mp e \sin \delta)\, d\delta \qquad (16)$$

To illustrate with a specific example, let $\alpha = 57\frac{1}{2}°$, $\delta = 30°$, $h = 448.3$ feet, and $e = 39.2$ feet; and let the dip be in a direction opposite to the slope of the hillside. Then from equation (10), $t = 189.05 + 33.95 = 223$ feet. Now let it be assumed that the errors of observation in strike and dip were as small as 1 degree. Substituting these errors as increments, in place of the differentials of α and δ, in equation (16), we have:

$$d\alpha = d\delta = \Delta\alpha = \Delta\delta = 1° = .01745$$

$$dt = .01745\,[120.44 + (327.44 - 19.60)] = 7.47$$

$$\frac{dt}{t} = \frac{7.47}{223} = .033 = 3.3 \text{ per cent, possible error in thickness.}$$

Thus, even though the geographic measurements are perfect, the stratigraphic thickness in this simple homoclinal sequence may have any value between 216 and 230 feet. If it is thought that the errors in α and δ were no larger than 1 degree, the thickness might be written as $t = 223 \pm 7$ feet.

The relative importance of strike and dip measurements may also be determined by utilizing the well-known principle of equal effects, which in fact is the only means of solving an otherwise indeterminate problem. Under this assumption,

$$\Delta t = n \frac{\partial t}{\partial \alpha} \Delta\alpha = n \frac{\partial t}{\partial \delta} \Delta\delta$$

where n equals the number of independent variables, in this case two.

It therefore follows that

$$\Delta\alpha = \frac{\Delta t}{n \dfrac{\partial t}{\partial \alpha}} \text{ and } \Delta\delta = \frac{\Delta t}{n \dfrac{\partial t}{\partial \delta}}$$

Now let the maximum allowable error in t be 5 per cent, that is,

$$\Delta t = 11.15$$

Then

$$\Delta\alpha = \frac{11.15}{2 \dfrac{\partial t}{\partial \alpha}} = \frac{11.15}{240.87} = .04629 = 2.6°$$

And

$$\Delta\delta = \frac{11.15}{2 \dfrac{\partial t}{\partial \delta}} = \frac{11.15}{615.68} = .01811 = 1.0°$$

These answers reveal two important facts: (1) The dip has to be correct to 1 degree in order that the stratigraphic thickness shall be correct to 5 per cent; and (2) the measurement of the dip is more than twice as critical as the measurement of the strike. The absolute magnitudes of these figures, of course, apply only to the problem in hand, but they show clearly that all stratigraphic measurements require an evaluation of this kind.

Folded rocks, however, present more involved problems, due largely to a lack of knowledge regarding the curvature of the folds. It has already been shown that the method of evolute and involutes largely obviates this source of error but is still affected by original errors in the determination of strike and dip. It therefore follows that the construction of profiles and the measurement of stratigraphic thickness by the method of evolute and involutes are subject to errors of about the same order as those shown to exist in the measurement of stratigraphic dimensions in a homoclinal sequence. The errors, however, in the computation of stratigraphic dimensions where observations are utilized in pairs, regardless of the construction or formula that is employed, are much greater; and as the true answer is indeterminate, no method is known for evaluating the possible error. Therefore differences, rather

than errors, are the only definite figures that can be cited in comparing one construction or formula with another.

The writer has used four methods to measure stratigraphic thickness in parallel folds, utilizing two observations of differing strikes and dips. The first, called the method of mean strikes and dips, is the oldest and best known. The other three methods, devised by the writer, may be called the method of integrated mean trigonometric functions, the method of skew-line normals, and the method of integrated mean strikes and dips, as proposed in this paper. It may be of interest to compare the results obtained from the use of these four methods.

The following problem has been used by the writer in previous publications to illustrate methods under discussion. To avoid new computations, it will be used again. Let the strike and dip of the planes tangent to two stratigraphic surfaces at A and B be N. 35° E., 10° S.E., and N. 70° E., 50° S. The direction of the traverse is S. 5° E., the slope of the hillside is 5°, the slope distance is 450 feet, and the rocks dip in a direction opposite to that of the hillside. Assuming the existence of parallel folding, it is required to find the stratigraphic thickness. The following answers to this problem are obtained by the four methods mentioned above:

Method of mean strikes and dips	223 feet
Method of integrated mean trigonometric functions	243 feet
Method of skew line normals	256 feet
Method of integrated mean strikes and dips	251 feet

Any, or none, of these answers may be correct. The difference between the smallest and the largest is 28 feet, which is about 12½ per cent of the smallest. The mean value is approximately 243 feet, but the true thickness is indeterminate.

From these considerations the reader may be led to believe that the measurement of sections, using observations in pairs, is a waste of time. Fortunately the situation is better than it seems. First it must be remembered that the problem above cited and solved is an extreme example, involving large changes in strike and dip, and a considerable distance between the initial and terminal points of the traverse. Commonly the changes in strike and dip, particularly in strike, are smaller than those cited; if outcrops are sufficiently plentiful, the measurements may be made at much shorter intervals. Moreover, a check can often be obtained by selecting pairs of observations in such a manner that different computations may be made over two or more zig-zag routes through different sets of stations. Finally, it is to be remembered that the total stratigraphic thickness is commonly the sum of a number of partial thicknesses. If an error is present in one of these parts of the section, due to some unusual type of curvature of the beds, it is likely to be compensated in some of the other parts. All these conditions serve materially to improve the overall accuracy of the results.

The differences obtained by various methods that utilize observations in pairs have already been given. The true value of the stratigraphic thickness, however, is indeterminate, owing to the unproved and unprovable assumptions that have to be made regarding curvature. Therefore only estimates, instead of determinations, of error can be cited. Under the most favorable conditions, where the dif-

ferences in strike and dip are not large, where the distance between stations is not great, and where the total thickness is the sum of a number of partial thicknesses, the error may not exceed 10 per cent and may actually be less. But under unfavorable conditions, characterized by a lack of the conditions just postulated, the error may be much greater, approaching or even exceeding 100 per cent.

CONCLUSIONS

Structural profiles that are meant to portray accurately the curvature of parallel folded strata, and precise measurements of stratigraphic dimensions, should be based on more than two structural observations, and preferably upon many observations considered as a group. The graphic method of evolute and involutes, though restricted in scope, is offered as a means of securing the best possible results from the data available.

Structural observations, however, must often be utilized in pairs, particularly where the strike and dip vary from point to point. If these variations are not large, of if the intervals of computation are small, the old method of inserting mean values or the strike and dip in some homoclinal formula is the simplest and best. If the point-to-point variations in strike and dip are large, or if the two observations are far apart, the method described in this paper constitutes a simple scheme for utilizing graphically the available data to the best advantage. The method also shows clearly when its use is warranted and when it is not.

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